Project Title: Experimental Neutrino Physics
Application/Institution: Drexel University
Street Address/City/State/Zip: 3201 Arch St., Philadelphia, PA 19104

Principal Investigator: Charles Lane
Postal Address: 3141 Chestnut St. 12-816, Philadelphia, PA 19104
Telephone number: (215) 895-1545
Email: lane@duphy4.physics.drexel.edu

DOE/Office of Science Program Office: Office of High Energy Physics
DOE/Office of Science Program Office Technical Contact: Dr.
Alan Stone

1 Introduction

Over the lifetime of the DOE grant supporting experimental particle physics at Drexel University, our focus has been primarily on cutting edge neutrino physics, both non-accelerator (KamLAND and Double Chooz) and more recently, accelerator based (LBNE).

This final report will primarily focus on work and results over the past few years, since previous work has been the subject of continuation and renewal reports that contain considerable detail. Some older work has been summarized in this report in the interests of providing context for the more recent efforts.

Please note that experimental contributions are from Prof. J. Maricic (now at the University of Hawaii, Manoa), Prof. C. E. Lane, graduates and undergraduates, with support from NSF and DOE.

2 KamLAND

Drexel has been involved in the KamLAND experiment from the early proposal stages until recently, providing backup acquisition electronics, analysis of nucleon decay data (Dr. Tatjana Miletic's dissertation), and most recently deploying the Optical Finder calibration module on the KamLAND 4π calibration deployment system.

Our participation in KamLAND has been during a period in which KamLAND produced the first evidence for reactor neutrino oscillations[1], followed by a measurement of the spectral distortion from oscillation of reactor neutrinos[2] which has yielded a very accurate measurement for the Δm_{12}^2 neutrino mass parameter, (Fig. 1).

KamLAND also produced the first signs of geo-neutrinos[4], and improved limits on neutron decay to neutrinos[5], both of which are measurements at energies that are inaccessible by large water Cherenkov detectors.

2.1 Optical finder

One of the challenges of detectors such as KamLAND is to accurately reconstruct the position of events inside the detector. This reconstruction is subject to systematic error. To reduce reconstruction error, calibration sources are deployed within the detector, and the resulting events analyzed.

Figure 1: KamLAND reactor anti-neutrino spectrum[3], converted to an L/E_ν plot to show the effects of oscillation.

The source deployment system has to be inserted through a narrow pipe into the detector, and is often at the end of a long lever arm. As a result, calibration deployment accuracy is often the limiting factor in position-related detector systematic errors, and when the response of the detector is position dependent, the energy reconstruction and trigger efficiency is subject to the systematic error that comes from source deployment position error.

The Optical Finder (OF) is a small light pulser that emits back-to-back synchronous beams of light, so that its position inside a detector can be determined using techniques that are simple, robust, and independent of the usual event reconstruction. When attached to a calibration deployment system, the goal of the OF is to provide a precise measurement of the deployment position (within 1–2 cm).

The first motivation for developing the OF came from the Double Chooz experiment (mentioned below), where reduction of systematic errors is of great importance. However, we realized that KamLAND was reaching the point where its reactor neutrino results were limited primarily by systematic errors rather than statistical errors, and so the use of an OF could also be

beneficial on KamLAND.

Development of the OF prototype consisted of several components:

- testing LED illumination angular distribution, by graduate student Nick Ridella
- absolute measurement of LED light levels (in terms of produced photons) to predict safe light levels in KamLAND (JM and CL)
- evaluation of various LEDs to choose appropriate brightness, fast response LEDs and angular response (we needed it to be as symmetric as possible) for which we constructed a large dark room (3m x 1.5 m x 2.5 m) and equipped with a row of PMTs in order to characterize angular LED response by Nick Ridella
- development of the electronic circuit with different pulsing rates for the three flashing LED pairs with variable intensity with an externally controlled magnetic switch to preserve battery life, by engineer Wolf Nadler
- design of the OF housing that is liquid tight (at 3 atmospheres) and satisfies material compatibility and stringent cleanliness requirements for which we constructed a temporary clean room

The original design plan used 3 LEDs and right angle mirror prisms to generate symmetric back to back beams. However, measurements in the dark box with the first prototype revealed that the flaring of the LED light produced light beams were half circle shaped, with the highest intensity inside the half circle, producing an offset in the reconstruction (please see the attached report at the KL collaboration meeting in Amsterdam 2010 about this issue). So we decided to use pairs of LEDs for each back-to-back beam and carefully machine the OF housing to position LEDs back-to-back.

2.2 LEDs

A number of LEDs were evaluated and several LEDs were tested, both wide and narrow angle LEDs. Detailed measurements with PMTs in the large dark room revealed that there is a slight azimuthal asymmetry in the produced light and that peak is sometimes offset from the zero degrees (central axes of the LED), so we had to make proper LED selection. Figures 2, 3 and 4

show the angular response for Nichea NSPB520S and NSPB320BS that both had about 2 ns rise time.

Figure 2: Angular response of Nichea NSPB520S

We have also determined absolute light levels in terms of total number of produced photons as a function of driving voltage. The set-up used had a fixed 2-inch PMT at a small distance facing the LEDs under test. The picture of the set-up is shown in Fig. 5.

2.3 OF housing design and prototype fabrication

The OF housing for KL had to be made of compatible materials, avoid shadowing, and maintain liquid tightness. So we built a housing at the Drexel machine shop from solid stainless steel with a Teflon O-ring for liquid tightness. Each of the LEDs protruded through the walls and the top and bottom of the housing was covered with an acrylic window sealed with compatible epoxy (Double Bubble Red). The OF attached to the 4π system via a screw and special safety pin. In addition, we tethered the OF with a stranded ultra clean cable that was also used for miniCal z -axis calibration. Figure 6 shows the OF ready for deployment with the tethering cable attached. Figure 7 shows the interior of the OF with the circuits that drive LED pulses.

Figure 3: Angular response along one (x-axis) of Nichea NSPB320BS

Figure 8 shows a picture of the temporary clean room that we built for OF assembly and cleaning. Finally, Fig. 9 shows the schematic diagram of the circuit used to drive the LED pulses.

The first test of an OF prototype device in a detector took place in July 2011 in KamLAND, using the KamLAND 4π calibration system. While the resulting data from the prototype was not very useful for improving calibration accuracy, much was learned about the triggering conditions needed for operation of the OF, as well as a much better understanding of the reconstruction needed to extract calibration positions.

The start of KamLAND-Xen operation has halted extensive calibration deployments for the immediate future, but the OF will be used in Double Chooz within the next year.

For the purpose of calibrating in Double Chooz we had to change the housing, since stainless steel housing is too heavy to be supported by the Double Chooz FV calibration device (articulated arm or AA). The new OF housing is made of polycarbonate (Lexan) and nearly neutrally buoyant. We conducted tests with OF housing attached to AA at Argonne National Lab's high bay building in April of 2012. The figure depicting the new acrylic housing including test in water with the OF are shown in Fig. 10 and Fig. 11.

Figure 4: Angular response along one (y-axis) of Nichea NSPB320BS

For the purpose of deployment in DC, changes were made to the electronic board that drives 3 pairs of LEDs. A single circuit is used in the updated design to achieve greater level of compactness.

Graduate student Erica Smith ran simulations to determine the potential of the OF in Double Chooz. She simulated a directional light source in the DC GEANT4 simulation and varied the opening angle of the LEDs. The goal was to determine the optimal opening angle for the LEDs and various cuts on the PMTs with the signal that would lead to the highest level of accuracy. Figure 13 shows the positioning uncertainty for the OF located at radial location 1 m from the detector center as a function of LED opening angle and how usage of different cuts affects the reconstructed accuracy of the simulated light beams. Figure 12 shows the reconstruction uncertainty for two different choice cuts for OF positioned at $z = 1000$ mm above the detector center.

From this simulation work we realized that a simple reconstruction scheme does not work so well in the cylindrical geometry of Double Chooz detector, requiring a more elaborate calculation scheme that would take into account the projected intersection of the light cone and the detector cylinder.

Another set of simulation studies was conducted by Ned Damon who used

Figure 5: Set-up to test and quantify absolute light levels for the LEDs used for OF

the geometry of the DC GEANT4 simulation to access shadowing and absorption and determine the positions to be calibrated. In addition, postdoc Dr. Stefano Perasso conducted a study using captures on Gd in the target to study uniformity and consequently how finely we need to calibrate and how well need to measure the position. The two maps (z and ϕ *vs.* cylindrical radius) will be used to select the positions where to deploy the sources. Calibration data taken so far have been used to test the position reconstruction algorithm.

The result of comparison to calibration data shows that events are reconstructed mainly inwards, the distance to the real position depending on the source position. Figure 14 show reconstructed energy of the Gd peak for z *vs.* radius and for angle *vs.* radius, and will be used to choose points for source deployment in the detector.

2.4 AA enclosure

One of the main concerns when working with Gd loaded scintillator is maintaining its stability and keeping it under a nitrogen atmosphere at all times. Any significant contact with oxygen (more than 50 ppm) leads to yellowing of

Figure 6: OF ready for deployment; the look from the outside

the scintillator and a decrease in transparency and light yield. As part of the overall AA and OF effort, we supported an effort to design, build and test a gas and light tight glovebox extension to preserve the nitrogen atmosphere during FV calibration in DC. The glove box extension has been built and tested. At this point it is functional with a separate nitrogen flow control, and is flushing well, although some minor leaks still need to be sealed. It will be ready for the AA deployment later this fall. Figure 15 shows a CAD drawing of the glovebox extension with FV device inside.

Figure 7: OF interior: three LED circuits visible.

Figure 8: OF clean room in preparation for deployment in KamLAND.

Figure 11: OF housing attached to the DC FV calibration system and submerged in water for test of motion and buoyancy.

Figure 12: Reconstructed position using PMT charge information from the OF directional light cones as a function of LED opening angle for OF positioned at $x = 1000$ mm, $y = 0$, $z = 0$. Two figures show cases when charge information from all PMTs is used, vs. charge information from the PMTs who are within 1σ of the light cone. Reconstruction accuracy is much better when charge information from all PMTs is used.

Figure 13: Reconstructed position using PMT charge information from the OF directional light cones as a function of LED opening angle positioned at $x = 0$, $y = 0$, $z = 1000$ mm. Two figures show cases when charge information from all PMTs is used, vs. charge information from the PMTs who are within 1σ of the light cone. Reconstruction accuracy is much better when charge information from all PMTs is used.

Figure 14: Reconstructed energy of Gd peak for different locations in the detector shown for the case of z vs. radius and for the case of azimuthal angle vs. radius. There is a noticeable variation in the reconstructed position and events tend to be reconstructed inward.

Figure 15: Conceptual and technical drawing of the glovebox extension that can fit AA.

3 Double Chooz

We have been active participants in the Double Chooz experiment over many years, areas of Drexel responsibility have included:

- Refurbishing Double Chooz inner-veto PMTs (R1408's recycled from the IMB experiment, by way of Super-K)
- Design and production of a new compact PMT base with expanded linear operation for the inner-veto PMTs
- Design of an articulated arm calibration deployment system
- Design, construction and installation of Front-End (FE) electronics
- Invention of an analog pulse stretcher, implemented in the FE, for summation of PMT charge for triggering purposes
- Prototyping an Optical Finder (mentioned above), also for use on Double Chooz, to improve calibration precision
- Analysis of Double Chooz neutrino data to extract neutrino directionality.

Double Chooz has recently published[6, 7] results that indicate a non-zero value of θ_{13} , and will be obtaining improved results when the Double Chooz near detector starts operation in early 2013. Unlike other reactor θ_{13} experiments, Double Chooz has had some 'reactors off' running, which is invaluable for background determination. The publication of the Double Chooz 'off-off' analysis is in preparation, and will be submitted for publication very shortly.

3.0.1 Pulse filtering

Some of the electronics developments on Double Chooz are a culmination of work previously started on KamLAND. In particular, it was noted on KamLAND that there were problems with PMT pulse overshoot and recovery times that created difficulties for DAQ and trigger systems. The cause of the most problematic overshoot issues were in the design of the PMT bases, already installed in the detector and inaccessible. Our goal was to use external filtering electronics to remove or mitigate the overshoot problems.

Figure 16: Pole-zero cancellation circuit input (showing RC effects) and output.

Over the years, we investigated a variety of possible techniques to deal with PMT pulse overshoot, including pole-zero cancellation, low-pass feed-forward cancellation, a high-pass filter optimized for pulse response, and transconductance feedback baseline restoration.

The pole-zero cancellation worked for short-time scale overshoot (see Fig 16), but was unable to improve the very long timescale KamLAND overshoot response. Low-pass feed-forward cancellation required much hand-tuning, but was ultimately used in prototypes of a new KamLAND DAQ/trigger system.

Aside from PMT base design problems, the pulse overshoot is a simple result of using a high-pass filter on the PMT signal, such as a capacitor to block the PMT HV. The high-pass filter approach was based on the well-known Sallen-Key topology, but with characteristics that were optimized for minimal pulse overshoot, by more closely matching the gentle “Gaussian filter” response. This filter was prototyped, and found to behave as expected: the overshoot was canceled to first order, but with a small “bump” much later from 2nd order filter response.

The transconductance feedback technique, however, proved to have the best separation of pulses from the low frequency effects (overshoot, baseline offset) that were canceled, and was clearly separated from the critical signal pathway, and thus was selected for use in the Double Chooz Front-End.

3.0.2 Pulse Stretcher

Scintillation detectors that have a generally spherical geometry, such as KamLAND and Double Chooz, have the characteristic that the total light collected by the PMTs is proportional to the ionization energy deposition. If the light attenuation by the scintillator is small, then the total light signal is independent of event location inside the detector.

Having a position independent measure of event energy is an important tool for triggering a neutrino detector, particularly when one wishes to remove any systematic effects of trigger inefficiencies.

On large detectors such as KamLAND, the photons from an event are spread out over many PMTs, most PMTs receive either zero or one photon, so simply counting PMT ‘hits’ gives a reasonable measure of event energy.

On smaller detectors, such as Double Chooz, many of the PMTs will receive multiple photons, so summing the PMT charge is needed to get a position independent measure of deposited energy. Unless the detector is very small, however, the light propagation time in the detector will ensure that the PMT pulses do not coincide, making a total charge summation more difficult.

An analog pulse stretcher circuit was developed as part of the Double Chooz Front-End electronics, with the goal of mitigating the effect of PMT pulse time offsets, while giving a more accurate PMT charge summation for detector triggering.

The basis of the pulse stretcher is to combine an input pulse with the delayed and inverted reflection of the pulse from a delay line, putting both pulses into a charge integrator circuit. The initial pulse deposits charge in the integrator, resulting in an amplitude proportional to the pulse charge, then the later inverted pulse removes the pulse charge (see Fig. 17 for the stretcher part of the Double Chooz FE schematic, and Fig. 18 for an oscilloscope capture of the stretcher in operation).

Since the pulse stretcher has no internal threshold or nonlinear components, the response is linear up to the output range of the op-amps (see Fig. 19).

Figure 17: Schematic of the Double Chooz pulse stretcher developed at Drexel. The width of the stretched pulse is determined by the delay line, which has multiple taps. The baseline restoration feedback is not shown. The pulse input is on the left.

Figure 18: Double Chooz pulse stretcher performance, showing the stretched output pulse (top) that results from a PMT pulse input (bottom).

Stretcher

Figure 19: Double Chooz pulse stretcher performance, showing output amplitude as a function of input charge.

4 Double Chooz Neutrino Directionality

(Dissertation topic for Ms. Erica Caden)

4.1 Position Reconstruction

In order to make a measurement of neutrino directionality, one must first ensure that the reconstructed positron and neutron positions are correct. This can be done by verifying the reconstructed positions of calibration source deployments. In Double Chooz, we currently have two calibration systems: a Z-axis “fish-line” system and a guide tube through the gamma catcher region of the detector. Data obtained from calibration source deployments in both systems is used to correct the reconstruction algorithm.

The z correction is obtained first by measuring the discrepancy between the reconstructed and known positions from sources deployed in the Z-axis system. The correction is a function of both position and energy of the source.

$$f(Z, E) = -0.1952 + (0.01959 + 0.00378 \cdot E) \cdot x \quad (1)$$

$$+ 0.00515 \cdot x^2 + (0.04187 - 0.00133 \cdot E) \cdot x^3 \quad (2)$$

This correction is then applied to the data from the guide tube system. The guide tube extends along the Y-axis, and provides our correction as a function of R^1 . We can also correct any residual difference in Z as a function of R. After these corrections are applied, the difference between the known and reconstructed deployment position is less than 2 cm, across the whole detector.

4.2 Directionality with Double Chooz

We first define the reactor-detector vector:

$$\vec{X}_{RD} = \vec{X}_{Detector} - \vec{X}_{Reactor} \quad (3)$$

For each neutrino candidate i , we have the reconstructed delayed and prompt vertices $\vec{X}_n^i$ and $\vec{X}_e^i$. We can construct the neutrino candidate displacement

¹ $R = \sqrt{X^2 + Y^2}$

Figure 20: True and Reconstructed Guide Tube Source Positions

vector:

$$\vec{X}_{en}^i = \vec{X}_n^i - \vec{X}_e^i \quad (4)$$

$\cos(\theta)$ between the two unit vectors should tend more towards +1 than -1 :

$$\cos(\theta) = \hat{X}_{en}^i \cdot \hat{X}_{RD} \quad (5)$$

We then define $\vec{p}$ as the average of the neutrino candidate displacement unit vector:

$$\vec{p} = \frac{1}{N} \sum_{i=1}^N \hat{X}_{en}^i \quad (6)$$

The components of $\vec{p}$ are Gaussian and have width P . The average distance between the prompt and delayed candidates and errors on $\vec{p}$ indicate how well we can locate the neutrino candidate source.

The average neutrino candidate direction, in the detector's coordinate system, is

$$\vec{p} = (-0.0064, -0.057, 0.0076) \text{ mm.}$$

Because of the symmetry of the Double Chooz detector's cylindrical geometry, P is expected to be the same for all directions. We can calculate the

azimuthal angle of the neutrino source:

$$\phi = \tan^{-1} \left(\frac{p_y}{p_x} \right) = -96^\circ.$$

The possibility of reconstructing the direction of the neutrino candidate source depends on the error on the average angle, $\Delta\phi$.

$$\Delta\phi(1\sigma) = (P/l)/\sqrt{N} \quad (7)$$

We measured the average neutron candidate displacement to be 1.64 cm. The total width of the prompt and delayed candidate vertex reconstruction has been measured to be 15.75 cm.

With $N = 8347$ events, we can locate the neutrino candidate source to within $\Delta\phi = 6^\circ$.

Figure 21: Tendency of neutrinos to point along reactor-detector direction.

5 LBNE

Over the past several years, we have been involved in the Water Cherenkov (WC) option for the LBNE far detector[8], primarily in testing PMTs as part of the overall PMT selection and characterization effort, developing prototyping, testing and simulating Winston-cone style light collectors for the PMTs to improve light collection efficiency (and reduce cost), and contributing to the LBNE near-detector (LBNE-ND) muon monitoring systems development.

5.1 Light Collectors

The LBNE WC option included several possible means of improving light collection without the use of additional (expensive) PMTs.

- Wavelength shifting plates, similar to those used in the IMB-II experiment, to convert Cherenkov photons and channel them to a PMT.
- A wavelength shifting coating over the face of PMTs, making a better match between the PMT quantum efficiency and the incoming photon wavelength
- ‘Winston’ style non-imaging reflector cones, to increase the effective area of the PMTs at the cost of some acceptance solid-angle.

At Drexel, we worked on the Winston Cone (WC) reflectors[9]: simulating their effects on a small scale with ray tracing for a single PMT, as well as large-scale simulations to see the effect on event reconstruction in the LBNE WC far detector. In addition, we produced prototype WC reflectors, starting from geometric calculations to CAD models that were used by manufacturers to produce plastic reflectors, which were then coated with aluminum or silver.

One difficult issue with WC reflectors was the material compatibility between the WC substrate, the reflective material, and the ultra-pure water in the detector. Aluminum was near ideal in terms of the UV reflectivity desired for Cherenkov light, but it would not survive in contact with water, and for long term (10 years) use in a detector the reflector would have to be put inside a plastic sandwich that would attenuate the UV light. We investigated the use of silver mirrors, which could withstand long-term immersion, as long as there was very low sulfur content in the water, but had lower UV reflectivity.

The possibility of rhodium-coated reflectors was under consideration when the WC option of LBNE was rejected, so was never fully investigated. Certainly, rhodium coatings would be more expensive than silver or aluminum, but the improvement in performance might have made it worthwhile.

5.2 LBNE-ND

The LBNE-ND effort is still at an early stage, but still well in advance of implementation as part of the overall LBNE experimental effort.

Much of the work has been concentrated on Michel Electron Detectors (MEDs), a system of small Cherenkov detectors placed downstream of the neutrino beamline decay pipe, between layers of ‘blue block’ absorbers. The muons that stop in the MEDs provide a measure of a particular energy range of the resulting muons after pion decay, related to the neutrino flux as a function of energy.

Another important function of the MEDs is to provide a measure of the fraction of “wrong sign” muons. The baseline MED design uses graphite absorbers around the MEDs, with ^{16}N β -decays registering in the MEDs to measure μ^- fraction.

Over the past six months we have investigated using MEDs that have water with a dissolved salt[10] (probably CaCl_2 , but other salts with high- Z elements are possible), to capture the stopping μ^- s with a shorter lifetime, so that the time structure of the Michel electron signal gives a measure of the muon charge composition.

We have produced small MED counters for testing with cosmic-rays, as part of an undergraduate research project, however there is much work still to be done to improve these counters, since the signal rate from cosmic rays is quite low.

One early conclusion is that PMT after-pulsing will present a significant challenge to MEDs, because the timescale for the muon decay signal and of PMT after-pulsing is quite similar. For low-rate cosmic rays, PMT after-pulsing effects can be minimized by using a coincidence of PMTs viewing a single MED, but with an intense muon beam pulse at the LBNE-ND, such single-pulse coincidence techniques are unlikely to be of use.

Other design work has been underway to produce a “gated” PMT base, that would be turned off during a beam pulse, but would be capable of being restored to operation within $\sim 1\,\mu\text{s}$ to capture the muon decay signal.

Testing was conducted with a 2-inch PMT, adjusting the voltage of a focusing grid to find the voltage range needed for gating. The next step is to use SPICE simulation to try gating circuit designs. At present, the use of a IGBT/QFET combination looks promising, but the challenges of switching $\approx 500\text{ V}$ within a microsecond are considerable.

6 Funds

There are no leftover funds from this project. All of the funding was utilized to advance experimental neutrino physics research within the grant period, which ended on 30 June 2012.

References

- [1] KamLAND Collaboration, K. Eguchi *et al.*, Phys.Rev.Lett. **90**, 021802 (2003), [hep-ex/0212021].
- [2] KamLAND Collaboration, T. Araki *et al.*, Phys.Rev.Lett. **94**, 081801 (2005), [hep-ex/0406035].
- [3] KamLAND Collaboration, S. Abe *et al.*, Phys.Rev.Lett. **100**, 221803 (2008), [0801.4589].
- [4] T. Araki *et al.*, Nature **436**, 499 (2005).
- [5] KamLAND Collaboration, T. Miletic, Nucl.Phys.Proc.Suppl. **221**, 374 (2011).
- [6] DOUBLE-CHOOZ Collaboration, Y. Abe *et al.*, Phys.Rev.Lett. **108**, 131801 (2012), [1112.6353].
- [7] Double Chooz Collaboration, Y. Abe *et al.*, 1207.6632, Accepted by Phys.Rev.D.
- [8] LBNE Collaboration, T. Akiri *et al.*, 1110.6249.
- [9] N. Buchanan *et al.*, LBNE-doc-5073, excerpted in Appendix.
- [10] C. Lane, LBNE-doc-5631, see Appendix.

A Reports, memos, publications

Winston Cones Update

Jelena Maricic, Stefano Perasso,
Chuck Lane
Drexel University

28

Winston Cones (WC) Design Overview

- Current prototype is Al coated (showed in the picture, fits on 10 inch PMT)
- Material coating considerations:
 - Aluminum – excellent reflectivity all the way to 200 nm, but incompatible with ultra pure water – must be covered by a protective layer (acrylic) and sealed
 - Silver – good reflectivity in sub 400 nm range, with two narrow absorption regions in sub 340 nm range; compatible with ultra pure water
 - Tests with Al and Ag prototypes at Pen didn't exhibit significant difference in performance
- Base material: acrylic, PVC (alternatives considered (but not tested if ultra pure water compatible): polycarbonate, PETg)
- Simulation studies on vertex and angular resolution with WC underway

Testing WCs with Cherenkov Light Source in Air at UPenn

Cherenkov source facing PMT directly

Results

With WC:

Without:

WC type	None	Aluminum	Silver	Wide
Rel. Eff.	1.0 (± 0.01)	1.45 (± 0.01)	1.43 (± 0.02)	3.05 (± 0.03)
TTS σ	1.49 ns (± 0.05)	1.45 ns (± 0.05)	1.49 ns (± 0.05)	1.72 ns (± 0.06)

Simulation Studies Strategy for WCs

- 1) Use untuned vertex reconstruction algorithms to optimize the size and shape of WCs*
 - Compare vertex and angular resolution in both high energy range (1 GeV) and low energy range (< 50 MeV) for electrons and muons generated uniformly in the detector

*Such elaborate procedure driven by cylindrical fiducial volume and just 2 m distance to it

- 2) Tune vertex reconstruction code to maximize performance
for the selected WC shape (optimize vertex and angular resolution with WCs)

- 3) **Ultimate goal** – check if we can match:

WCD 14% effective photocoverage (+ WCs)

to match performance of

WCD 20% effective photocoverage (no WCs)

and ideally to match performance of

Critical step

SK-II 20% effective coverage (already shown as a part of scaling studies for WCD and more difficult to show directly since it requires precisely tuned LBNE WCD MC)

in terms of

vertex and angular resolution, particle ID efficiency and background rejection efficiency

In this way, we will be much more confident that WCD with Winston cones can indeed reach its physics goals.

32

Simulation studies overview

- 1 GeV electrons and muons simulated using WCSim
- This version of WCSim (200 kton + 12 inch PMTs) has the following feature, important for WC studies:

- Polar angle dependent collection efficiency for photocathode implemented along with the hit position on the PMT face

This feature is important for us, since WCs tend to focus the light closer to the PMT equator compared to bare PMT, so any position dependent collection efficiency must be taken into account

Events reconstructed using available charge based vertex reconstruction code (developed by Andy Blake)

Study vertex and angular resolution with and without Winston cones

Simulation studies shown performed by S. Perasso@Drexel

33

Shape studies

- 4 WC shapes tested (varied height and acceptance angle)
- Same ellipsoidal profile, different height

Gain calculated
for uniformly
generated 1GeV
electrons and muons
in the FV

Gain vs. opening angle

Two representative shapes
shown
The rest of the preliminary
work shown for these
two WCs

34

Electrons at 1 GeV

12% photocoverage

$\Delta = \text{True_vertex} - \text{Recon_Vertex}$

$\alpha = \alpha_{\text{true}} - \alpha_{\text{recon}}$

Gain vs. opening angle

	No WC	WC1	WC2	WC3	WC4
Gain	1	1.52	1.42	1.48	1.34
$\delta(\text{RV} - \text{TV})$ [m]	1.91 ± 0.05	1.23 ± 0.03	1.23 ± 0.02	1.2 ± 0.02	1.35 ± 0.02
$\alpha(\text{RA} - \text{TA})$ [$^{\circ}$]	4.85 ± 0.17	5.53 ± 0.18	4.08 ± 0.13	4.68 ± 0.15	3.77 ± 0.12

35

Muons at 1 GeV

12% photocoverage

$\Delta = \text{True_vertex} - \text{Recon_Vertex}$

$\alpha = \alpha_{\text{true}} - \alpha_{\text{recon}}$

Gain vs. opening angle

	No WC	WC1	WC2	WC3	WC4
Gain	1	1.52	1.42	1.48	1.34
$\delta(\text{RV} - \text{TV})$ [m]	0.597 ± 0.02 7	0.706 ± 0.043	0.537 ± 0.030	0.62 ± 0.037	0.555 ± 0.032
$\alpha(\text{RA} - \text{TA})$ [$^{\circ}$]	2.01 ± 0.096	2.91 ± 0.15	1.97 ± 0.1	2.45 ± 0.129	1.91 ± 0.099

36

Vertex Resolution: 10% + WC2s vs. 14% no WC

1 GeV electrons

$\Delta = \text{True_vertex} - \text{Recon_Vertex}$

Preliminary

37

Angular resolution: 10% + WC2 vs. 14% no WC

Preliminary

1 GeV electrons

$\text{Alpha} = \text{Alpha_true} - \text{Alpha_recon}$

38

Vertex resolution: 10% + WCs vs. 14% no WC

Preliminary

1 GeV muons

39

Angular resolution: 10% + WCs vs. 14% no WC

Preliminary
1 GeV muons

$\text{Alpha} = \text{Alpha_true} - \text{Alpha_recon}$

Short term plans for Winston Cone development

- Converge on shape for 12" PMT based on high and low energy simulation studies
- Tune vertex reconstruction with WCs
- Calculate vertex and angular resolution and move toward particle ID studies
- Build a new prototype for 12" PMT
- Protect Al coating to prepare for water tests
- Compare Al and Ag coated prototype performance in water and make decision on material of choice
- Send Al coated samples to BNL for material compatibility testing
- Costing estimates – contact other vendors and obtain mass production quotes (current estimate based on response of vendors that produced prototypes)

Further Steps and Summary

- Two LC technologies being pursued in parallel
- Preliminary functional prototypes for WC and WLSP have been made and are being tested
- To do: prototypes for 12" PMT, material compatibility tests, costing
- Simulation studies are underway and will critically influence decision whether to use LCs for WCD and which LC to choose
 - Simulation vertex and angular resolution, particle ID efficiency and background rejection efficiency must meet the CDR requirements
 - Useful results for benchmark studies expected in spring/summer 2012.
- Decision whether and which LC to use in WCD will take place in April 2013, before CD-2.

An idea for Michel counters

C. Lane
Drexel University

Current scheme:

- Small water-Cherenkov counters to measure stopping muon rate via Michel electrons
- Surround with layer of graphite, so some μ^- are captured ($\sim 10\%$) and some ($\sim 10\%$) of those produce ^{12}B .
- ^{12}B β -decays (20ms halflife), 13MeV
- Detection of the ^{12}B decays gives a measure of μ^- content.

Another possibility

- Divide into two varieties of Michel detectors:
 - pure water: measure both μ^- and μ^+ .
 - water with “heavy elements” (Pb?, Ca?): the μ^- captures quickly, μ^+ has ‘normal’ $2.2\mu\text{s}$ lifetime.
 - Compare the number of Michel decay to get μ^-/μ^+ ratio.

$$\begin{aligned}\tau_{\text{vac}} &= 2.2\mu\text{s} \\ \tau_{\text{O}} &= 1.8\mu\text{s} \\ \tau_{\text{Ca}} &= 0.33\mu\text{s} \\ \tau_{\text{pb}} &= 0.07\mu\text{s}\end{aligned}$$

Requirements

- Need to count both μ^-/μ^+ in water, so must have sensitivity $\sim 10\mu\text{s}$ after beam pulse (otherwise μ^- capture on oxygen)
- For μ^- contamination of μ^+ beam: “disappearance mode” limits sensitivity
- But μ^+ contamination of μ^- beam: good sensitivity (only μ^+ signal in $\text{H}_2\text{O}+\text{Ca}$ counter)
- While other loading possible (Pb, Bi, etc., salts), suggest CaCl_2 : cheap, soluble, non-toxic, high-Z enough.

Advantage/Disadvantage

- Advantages:
 - Compare Michel decays to Michel decays: same (high) threshold, similar lifetimes.
 - Do not need to use precise Monte-Carlo simulation of ^{12}B beta range and Cherenkov signal to find μ^- detection efficiency.
 - “road salt is cheaper than machined graphite”
- Disadvantages:
 - Segmented or doubled number of detector elements
 - Same muon flux at each detector?
 - μ^- beam contamination measurement is “disappearance mode”, probably error limited.

Studying Neutrino Directionality with Double Chooz

E. Caden

*Department of Physics, Drexel University,
Philadelphia, PA, 19104, USA*

The first results from Double Chooz with 100 days of data measured $\sin^2(2\theta_{13}) = 0.086 \pm 0.051$. Backgrounds contribute significantly to the systematic uncertainty budget. Using the incoming neutrino directionality we will attempt to further separate the inverse beta decay signal from backgrounds. The CHOOZ experiment completed a similar analysis and found that the neutrino source can be located to within a cone of half-aperture of 18 degrees at the 68% C.L. We study the possible improvement of this result by Double Chooz.

1 Double Chooz

Double Chooz is a neutrino oscillation experiment in the French Ardennes. It is a reactor experiment, looking for a deficit of electron neutrinos. The probability that an electron anti-neutrino will be detected as an electron anti-neutrino is

$$P_{surv} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2 L/E), \quad (1)$$

where Δm^2 is the atmospheric mass splitting, L is the distance from the reactor cores to the detector in meters, and E is the energy of the anti-neutrino in MeV. Electron anti-neutrinos are produced by two 4.25 GW_{TH} reactor cores of the Chooz Nuclear Power Plant. Neutrinos are detected through the inverse beta decay reaction (IBD):

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (2)$$

The detector (fig. 1a), 1.05 km from the reactors, consists of a series of sub-detectors: the neutrino target, a gamma catcher region, a non-scintillating buffer, an inner veto region, and an outer veto cover. The innermost vessel is target, an acrylic vessel filled with 10.3 m³ of PXE and dodecane with fluors PPO and Bis-MSB. The target also contains Gadolinium at 0.1% concentration, to enhance the neutron capture probability. The gamma catcher is also filled with scintillating mineral oil, and is used to detect gammas escaping from the target. There are 390 photomultiplier tubes (PMTs) mounted in the buffer, which is filled with non scintillating oil. This region shields the target from radioactivity of the photomultiplier tubes. The inner veto, with 78 PMTs and filled with scintillator, vetoes cosmic-ray muons and spallation neutrons. The entire volume is then surrounded by low activity demagnetized steel. To also help in tagging muons, Double Chooz has an outer veto, which is sixty-four panels of scintillator strips and wavelength shifting fibers that tag the position and angle of incoming muons. The entire detector system is buried under 300 m.w.e of rock overburden, which acts as a natural shield against cosmic ray muons.

The signals are amplified by an analog Front End system, and events are triggered based on the summed charge of PMT groups exceeding an energy threshold. When triggered, waveforms from each PMT are digitized by Flash-ADC electronics with a custom, dead-time free acquisition system. After 100 days of physics data, 4121 neutrino candidates were found, when 4344 ± 165 were expected with no oscillation. This deficit leads to $\sin^2 2\theta_{13} = 0.086 \pm 0.051$ (stat + sys)¹. The result is shown in figure 1b.

(a) The Double Chooz detector system.

(b) Top: Measured and expected prompt energy spectra, including backgrounds. Bottom: Difference between data and no oscillation spectrum.

2 Neutrino Directionality

Measuring neutrino directionality depends on accurately knowing the position and angular distribution of the IBD reaction products: the positron and the neutron. Results presented here are relevant for anti-neutrinos produced by reactors, $E_\nu < 10$ MeV.

From Vogel and Beacom², the positron angular distribution is given by

$$\frac{d\sigma}{d\cos\theta} \simeq 1 + \beta a(E_\nu) \cos\theta_e \quad (3)$$

where θ_e is the angle between anti-neutrino and positron directions, β is the positron velocity, and a is the asymmetry coefficient. $a(E_\nu)$ is given by the competition of non-spin-flip (Fermi) and spin-flip (Gamow-Teller) contributions. In the limit where the mass of the nucleon is taken to be infinite ($1/m_n \approx 0$), $a(E_\nu) = a^{(0)}$,

$$a^{(0)} = \frac{f^2 - g^2}{f^2 + 3g^2} \simeq -0.102 \quad (4)$$

where f and g are the vector and axial-vector coupling constants, respectively taken to be 1 and 1.26. Taking the common assumption of relativistic neutrinos where $\beta \approx 1$, the average cosine weighted by the differential cross section is

$$\langle \cos\theta_e \rangle = \frac{1}{3} a(E_\nu) = -0.034. \quad (5)$$

The average positron angle is slightly backwards. The original CHOOZ collaboration calculated the mean positron displacement to be -0.05 cm with respect to the initial anti-neutrino interaction point³. The small displacement and negligible preferred scattering angle mean that the positron movement can be neglected. Accounting for the small kinetic energy of the neutron, the positron's energy depends on its scattering angle and is

$$E_e = (E_\nu - \Delta) \left[1 - \frac{E_\nu}{m_n} (1 - \cos \theta_e) \right] - \frac{\Delta^2 - m_e^2}{2m_n} \quad (6)$$

The neutron's kinetic energy then follows as

$$E_n = \frac{E_\nu (E_\nu - \Delta)}{m_n} (1 - \cos \theta_e) + \frac{\Delta^2 - m_e^2}{2m_n} \quad (7)$$

Conservation of momentum in the laboratory ($\vec{p}_p = 0$) leads to

$$\vec{p}_\nu = \vec{p}_e + \vec{p}_n. \quad (8)$$

Using

$$|p_e| \leq \sqrt{(E_\nu - \Delta)^2 - m_e^2} < E_\nu, \quad (9)$$

one can calculate that the neutron must be always be emitted in the forward hemisphere, relative to the incoming anti-neutrino direction. The maximum angle between the anti-neutrino and initial neutron directions was calculated in² to be

$$\cos(\theta_n)_{max} = \frac{\sqrt{2E_\nu\Delta - (\Delta^2 - m_e^2)}}{E_\nu}. \quad (10)$$

At the IBD threshold of 1.8MeV the neutron direction is purely forward and for reactor anti-neutrino energies (< 10 MeV) it is still mainly in the forward direction. Neutron diffusion preserves the incoming direction of the neutron. With each scatter, the average cosine with respect to the incoming direction is:

$$\langle \cos \theta_n \rangle = 2/3A \quad (11)$$

where A is the atomic number of the scattering nucleus. Therefore the direction is most preserved when scattering off Hydrogen, which has a large cross-section for neutron scattering at the relevant energy range.

Reconstructing the incoming neutrino's direction requires constructing a vector, $\vec{X}_{en}^i$, pointing from the positron's reconstructed position to the neutron's reconstructed position, where $\vec{X}_{en}^i = X_n^i - X_e^i$. Averaging this vector over all events gives:

$$\vec{p} = \sum_{i=1}^N \vec{X}_{en}^i \quad (12)$$

The cosine of the angle between $\vec{X}_{en}^i$ and a similar vector from the reactor to the detector $\vec{X}_{RD}$ should point more towards +1 than -1. This is a statistical measurement that improves with the number of neutrino candidates. The probability distribution of the components of $\vec{p}$ are Gaussian, with a width P . Because of the symmetry of the Double Chooz detector's cylindrical geometry, P is expected to be the same for all directions. Measuring $\vec{p} = (p_x, p_y, p_z)$, we can calculate the azimuthal and zenith angles of the neutrino source:

$$\begin{aligned} \tan \phi &= \frac{\bar{p}_y}{\bar{p}_x} \\ \tan \theta &= \frac{\bar{p}_z}{\sqrt{\bar{p}_x^2 + \bar{p}_y^2}} \end{aligned}$$

The possibility of reconstructing the direction of the neutrino source depends on the errors on the angles, $\Delta\phi$ and $\Delta\theta$. Using the gaussian nature of the components, $\Delta p_i = P/\sqrt{N}$, we calculate the errors to be:

$$\Delta \tan \phi = \sqrt{\left(\frac{P \cdot \bar{p}_y}{\sqrt{N} \bar{p}_x^2}\right)^2 + \left(\frac{P}{\sqrt{N} \bar{p}_x}\right)^2}$$

$$\Delta \tan \theta = \sqrt{\left(\frac{P}{\sqrt{N} \sqrt{\bar{p}_x^2 + \bar{p}_y^2}}\right)^2 \left[1 + \left(\frac{\bar{p}_y \bar{p}_z}{\bar{p}_x^2 + \bar{p}_y^2}\right)^2 + \left(\frac{\bar{p}_x \bar{p}_z}{\bar{p}_x^2 + \bar{p}_y^2}\right)^2\right]}$$

3 Previous work on Directionality and Double Chooz Improvement

The concept of reactor neutrino directionality was shown by the Gösgen, Bugey, and Palo Verde collaborations for segmented scintillator detectors. These measurements were made by observing the neutron in a segment farther away from the reactor than the segment where the positron was observed.

The first measurement of this kind using an unsegmented scintillator detector was by the CHOOZ collaboration, using the technique described above. With only ~ 2500 events, the neutrino source was located within a cone of 18° half-angle opening. As this is primarily a statistics driven measurement, Double Chooz is poised to greatly improve that result.

References

1. Abe, Y. *et al*, *Phys. Rev. Lett.* **108**, 131801 (2012).
2. Vogel, P. and Beacom, John F., *Phys. Rev. D* **60**, 053003 (1999).
3. Apollonio, M. *et al*, *Phys. Rev. D* **61**, 012001 (2000).
4. Hochmuth, K. *et al*, *Phys. Rev. D* **76**, 073001 (2007).

Reactor $\bar{\nu}_e$ disappearance in the Double Chooz experiment

Y. Abe,³⁰ C. Aberle,²¹ J.C. dos Anjos,⁵ J.C. Barriere,¹⁵ M. Bergevin,⁹ A. Bernstein,¹⁶ T.J.C. Bezerra,²⁸ L. Bezrukhov,¹⁴ E. Blucher,⁶ N.S. Bowden,¹⁶ C. Buck,²¹ J. Busenitz,² A. Cabrera,⁴ E. Caden,¹⁰ L. Camilleri,⁸ R. Carr,⁸ M. Cerrada,⁷ P.-J. Chang,¹⁷ P. Chimenti,³³ T. Classen,^{9,16} A.P. Collin,¹⁵ E. Conover,⁶ J.M. Conrad,²⁰ J.I. Crespo-Anadón,⁷ K. Crum,⁶ A. Cucoanes,^{25,15} M.V. D'Agostino,³ E. Damon,¹⁰ J.V. Dawson,^{4,36} S. Dazeley,¹⁶ D. Dietrich,³² Z. Djurcic,³ M. Dracos,²⁴ V. Durand,^{15,4} J. Ebert,¹¹ Y. Efremenko,²⁷ M. Elnimr,²⁵ A. Etenko,¹⁹ M. Fallot,²⁵ M. Fechner,¹⁵ F. von Feilitzsch,²⁶ J. Felde,⁹ D. Franco,⁴ A.J. Franke,⁸ M. Franke,²⁶ H. Furuta,²⁸ R. Gama,⁵ I. Gil-Botella,⁷ L. Giot,²⁵ M. Göger-Neff,²⁶ L.F.G. Gonzalez,³⁴ M.C. Goodman,³ J.T.M. Goon,² D. Greiner,³² N. Haag,²⁶ C. Hagner,¹¹ T. Hara,¹⁸ F.X. Hartmann,²¹ J. Haser,²¹ A. Hatzikoutelis,²⁷ T. Hayakawa,²² M. Hofmann,²⁶ G.A. Horton-Smith,¹⁷ A. Hourlier,⁴ M. Ishitsuka,³⁰ J. Jochum,³² C. Jollet,²⁴ C.L. Jones,²⁰ F. Kaether,²¹ L.N. Kalousis,²⁴ Y. Kamyshev,²⁷ D.M. Kaplan,¹³ T. Kawasaki,²² G. Keefer,¹⁶ E. Kemp,³⁴ H. de Kerret,^{4,36} Y. Kibe,³⁰ T. Konno,³⁰ D. Kryn,⁴ M. Kuze,³⁰ T. Lachenmaier,³² C.E. Lane,¹⁰ C. Langbrandtner,²¹ T. Lasserre,^{15,4} A. Letourneau,¹⁵ D. Lhuillier,¹⁵ H.P. Lima Jr,⁵ M. Lindner,²¹ J.M. López-Castanõ,⁷ J.M. LoSecco,²³ B.K. Lubsandorzhev,¹⁴ S. Lucht,¹ D. McKee,¹⁷ J. Maeda,³¹ C.N. Maesano,⁹ C. Mariani,^{8,35} J. Maricic,¹⁰ J. Martino,²⁵ T. Matsubara,³¹ G. Mention,¹⁵ A. Meregaglia,²⁴ T. Miletic,¹⁰ R. Milincic,¹⁰ H. Miyata,²² Th.A. Mueller,²⁸ Y. Nagasaka,¹² K. Nakajima,²² P. Novella,⁷ M. Obolensky,⁴ L. Oberauer,²⁶ A. Onillon,²⁵ A. Osborn,²⁷ I. Ostrovskiy,² C. Palomares,⁷ I.M. Pepe,⁵ S. Perasso,¹⁰ P. Perrin,¹⁵ P. Pfahler,²⁶ A. Porta,²⁵ W. Potzel,²⁶ J. Reichenbacher,² B. Reinhold,²¹ A. Remoto,^{25,4} M. Röhling,³² R. Roncin,⁴ S. Roth,¹ Y. Sakamoto,²⁹ R. Santorelli,⁷ F. Sato,³¹ S. Schönert,²⁶ S. Schoppmann,¹ T. Schwetz,²¹ M.H. Shaevitz,⁸ S. Shimojima,³¹ D. Shrestha,¹⁷ J.-L. Sida,¹⁵ V. Sinev,^{14,15} M. Skorokhvatov,¹⁹ E. Smith,¹⁰ J. Spitz,²⁰ A. Stahl,¹ I. Stancu,² L.F.F. Stokes,³² M. Strait,⁶ A. Stüken,¹ F. Suekane,²⁸ S. Sukhotin,¹⁹ T. Sumiyoshi,³¹ Y. Sun,² R. Svoboda,⁹ K. Terao,²⁰ A. Tonazzo,⁴ M. Touns,⁸ H.H. Trinh Thi,²⁶ G. Valdivieso,⁵ C. Veyssiere,¹⁵ S. Wagner,²¹ H. Watanabe,²¹ B. White,²⁷ C. Wiebusch,¹ L. Winslow,²⁰ M. Worcester,⁶ M. Wurm,¹¹ F. Yermia,²⁵ and V. Zimmer²⁶

(Double Chooz Collaboration)

¹III. Physikalisches Institut, RWTH Aachen University, 52056 Aachen, Germany

²Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA

³Argonne National Laboratory, Argonne, Illinois 60439, USA

⁴APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France

⁵Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ, cep 22290-180, Brazil

⁶The Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA

⁷Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, CIEMAT, E-28040, Madrid, Spain

⁸Columbia University; New York, NY 10027, USA

⁹University of California, Davis, CA-95616-8677, USA

¹⁰Physics Department, Drexel University, Philadelphia, Pennsylvania 19104, USA

¹¹Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany

¹²Hiroshima Institute of Technology, Hiroshima, 731-5193, Japan

¹³Department of Physics, Illinois Institute of Technology, Chicago, Illinois 60616, USA

¹⁴Institute of Nuclear Research of the Russian Academy of Science, Russia

¹⁵Commissariat à l'Energie Atomique et aux Energies Alternatives, Centre de Saclay, IRFU, 91191 Gif-sur-Yvette, France

¹⁶Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

¹⁷Department of Physics, Kansas State University, Manhattan, Kansas 66506, USA

¹⁸Department of Physics, Kobe University, Kobe, 657-8501, Japan

¹⁹NRC Kurchatov Institute, 123182 Moscow, Russia

²⁰Massachusetts Institute of Technology; Cambridge, MA 02139, USA

²¹Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

²²Department of Physics, Niigata University, Niigata, 950-2181, Japan

²³University of Notre Dame, Notre Dame, IN 46556- 5670, USA

²⁴IPHC, Université de Strasbourg, CNRS/IN2P3, F- 67037 Strasbourg, France

²⁵SUBATECH, CNRS/IN2P3, Université de Nantes, Ecole des Mines de Nantes, F-44307 Nantes, France

²⁶Physik Department, Technische Universität München, 85747 Garching, Germany

²⁷Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA

²⁸Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan

²⁹Tohoku Gakuin University, Sendai, 981-3193, Japan

³⁰Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan

³¹Department of Physics, Tokyo Metropolitan University, Tokyo, 192-0397, Japan

³²Kepler Center for Astro and Particle Physics, Universität Tübingen, 72076, Tübingen, Germany

³³Universidade Federal do ABC, UFABC, São Paulo, Santo André, SP, Brazil

³⁴*Universidade Estadual de Campinas-UNICAMP, Campinas, SP, Brazil*

³⁵*Center for Neutrino Physics, Virginia Tech, Blacksburg, VA*

³⁶*Laboratoire Neutrino de Champagne Ardenne, domaine d'Aviette, 08600 Rancennes, France*

(Dated: August 30, 2012)

The Double Chooz experiment has observed 8,249 candidate electron antineutrino events in 227.93 live days with 33.71 GW-ton-years (reactor power $\times$ detector mass $\times$ livetime) exposure using a 10.3 m³ fiducial volume detector located at 1050 m from the reactor cores of the Chooz nuclear power plant in France. The expectation in case of $\theta_{13}=0$ is 8,937 events. The deficit is interpreted as evidence of electron antineutrino disappearance. From a rate plus spectral shape analysis we find $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$. The data exclude the no-oscillation hypothesis at 99.8% CL (2.9σ).

I. INTRODUCTION

In the three neutrino paradigm, there are three mixing angles that can be measured in neutrino oscillation experiments. For many years, the CHOOZ reactor neutrino experiment [1] had the best limit on the value of θ_{13} . Recently, the value of θ_{13} has been shown to be non-zero by the combination of fits to KamLAND and solar [2–4], MINOS [5], T2K [6] and, more precisely, by the new generation of reactor antineutrino disappearance experiments: Double Chooz [7], Daya Bay [8] and RENO [9].

The Double Chooz analysis is unique among reactor experiments in its fit to the energy spectrum. In the previous reactor measurements of θ_{13} , Double Chooz presented both a rate-only analysis and an analysis using both the rate and the shape of the energy spectrum, while Daya Bay and RENO presented rate-only analyses. The disappearance of reactor electron antineutrinos has a well-defined effect on the shape of that spectrum. The use of the energy distribution to constrain the oscillation parameters requires a good understanding of the energy response of the detector and of the accuracy of the Monte Carlo. That understanding is achieved through multiple calibration techniques, in time, space and energy.

This paper continues the analysis reported in [7] with a larger data set, a new energy scale definition, reduced background rates and improved systematic uncertainties. Additionally, the running period has been subdivided into a two-reactor-on period and a one-reactor-on period in the oscillation fit to help separate signal and background.

Reactor antineutrinos are observed using the inverse beta decay (IBD) reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ in which there is a positron whose signal is promptly seen, and a neutron, whose delayed signal is seen after a mean time of about 30 μs from its capture in the gadolinium-doped target. The prompt energy of the positron allows us to determine the antineutrino energy and observe the antineutrino spectrum. The energy deposited by the positron including annihilation is related to antineutrino energy $E_{\bar{\nu}_e}$ by $E_{\text{prompt}} = E_{\bar{\nu}_e} - T_n - 0.8 \text{ MeV}$ where T_n denotes the average neutron recoil energy and is small compared to $E_{\bar{\nu}_e}$.

The previous analysis represented 15.34 GW-ton-years of exposure, taking into account the reactor livetime and

the detector fiducial mass. Here we re-analyze that data set together with an additional 18.37 GW-ton-years giving a total of 33.71 GW-ton-years. In addition the analysis of 22.5 hours of both-reactors-off data allows a cross check of our estimates of the correlated and accidental backgrounds.

The structure of the paper is as follows. In Section II we review the experimental setup and detector. Section III covers the measurements and simulations of the Chooz reactors used to predict the unoscillated neutrino spectrum, as well as the model used to describe the detector. Event reconstruction including the energy determination of candidate events is described in Section IV. The steps that are used to identify reactor neutrino candidates are covered in Section V. Section VI presents the extraction of neutrino mixing parameters from the measured antineutrino rate and energy distribution.

II. DETECTOR AND METHOD DESCRIPTION

A. Overview

The Double Chooz detector system [10] consists of a main detector, an outer veto, and calibration devices (Figure 1). The main detector is made of four concentric cylindrical tanks with a chimney in the center at the top and is filled with liquid scintillators or mineral oil.

The innermost 8 mm thick transparent (UV to visible) acrylic vessel contains 10.3 m³ gadolinium loaded liquid scintillator called the ν -target (NT). The NT volume is surrounded by the γ -catcher (GC), a 55 cm thick Gd-free liquid scintillator layer in a second 12 mm thick acrylic vessel, used to detect gamma rays escaping from the ν -target. Outside the γ -catcher is the buffer, a 105 cm thick mineral oil layer. It shields from radioactivity of photomultiplier tubes (PMTs) and surrounding rock, and is one of the major improvements over the CHOOZ experiment [1]. The 390 10-inch PMTs [11–13] are installed on the inner wall of the stainless steel buffer tank to collect light from the inner volumes. These three volumes and PMTs constitute central detector system referred to as the inner detector (ID). Outside the ID, and optically separated from it by a stainless steel vessel, is a 50 cm thick inner veto (IV) liquid scintillator. It is equipped with 78 8-inch PMTs and functions as a cosmic muon

veto and as an active shield to spallation neutrons produced outside the detector. The detector is covered and surrounded by 15 cm of demagnetized steel to suppress external gamma rays. The main detector is covered by an outer veto system (OV) described in Section II G.

B. Radiopurity

All parts of the Double Chooz detector have been thoroughly screened for their content of radioactive isotopes prior to their installation. The screening was carried out by direct gamma spectroscopy with a variety of germanium detectors in underground laboratories. Among them were the large HPGe detector for the non-destructive radioassay at Saclay [14] and the GeMPI detector at Gran Sasso [15] with a sensitivity of about $10 \mu\text{Bq/kg}$ for U and Th. In addition, neutron activation analyses have been performed for dedicated parts of the inner detector: the acrylics for NT and GC vessels as well as the wavelength shifter PPO [16]. The irradiations were done at the FRM II research reactor in Garching, Germany by a thermal neutron flux of $1.63 \cdot 10^{13} \text{ cm}^{-2} \cdot \text{s}^{-1}$, with subsequent gamma spectroscopy in the Garching underground laboratory [17].

The PMT glass and cavern rock are the main sources of the gamma ray background. The PMT glass was made from low activity sands using a platinum coated furnace to reduce contamination. Radioactivity of the glass samples was measured during development of the low activity glass and production of the PMTs [18]. The average measurements were 13 ppb, 61 ppb and 3.3 ppb for ^{238}U , ^{232}Th and ^{40}K , respectively assuming radio-equilibrium, which are much smaller than regular PMT glass.

FIG. 1. A cross-sectional view of the Double Chooz detector system.

The design goal of Double Chooz concerning radiopurity is no more than ~ 0.8 accidental background events per day. Along with the radiopurity screenings, Double Chooz maintained strict clean-room conditions during the setup of the detector with an ISO-level up to 6. The analysis of BiPo coincidences in the detector data yields concentrations of U and Th in NT and GC below the design goal of 10^{-13} g/g . The accidentals rate is measured to be $< 0.5 \text{ d}^{-1}$, well below our design goal. The daily rate of correlated background events stemming from (α, n) -reactions of ^{210}Po on ^{13}C is estimated to be smaller than 0.020 d^{-1} (scaled from the result of KamLAND [19]), which is negligibly small compared to the neutrino signal.

C. Double Chooz Liquids

The CHOOZ experiment was limited in sensitivity by the optical instability of its gadolinium-loaded (Gd) scintillator [20]. Therefore a new type of metal loaded organic liquid scintillator was developed for Double Chooz [16]. The target scintillator used in the NT must fulfill the basic requirements of Gd solubility in the solvent of choice, optical transparency, radiopurity and chemical stability. In addition, the organic liquid must be compatible with the detector materials in contact with the scintillator, mainly acrylics. Safety considerations influenced the scintillator design as well.

Since the rare earth Gd does not dissolve in the required amount in the organic solvents used for liquid scintillators, a metalorganic complex is formed providing higher solubility. In particular, the complex of choice is a metal- β -diketone, $\text{Gd}(\text{thd})_3$, $\text{Gd}(\text{III})$ -tris-(2,2,6,6-tetramethyl-heptane-3,5-dionate). Such complexes are known for their stability and high vapor pressure. This allowed us to purify the material by sublimation reducing radioimpurities U, Th and K. The Gd concentration in the NT is 0.123% by weight, which corresponds to about 1 g/liter.

As scintillator solvent for the NT we have chosen an ortho-phenylxylylethane (o-PXE)/n-dodecane mixture at a volume ratio of 20/80. To shift the scintillation light into a more transparent region, wavelength shifters are added. In both scintillators we use PPO (2,5-diphenyloxazole) as primary fluor and bis-MSB (4-bis-(2-methylstyryl)benzene) as secondary wavelength shifter.

The light yield and density of the GC liquid (22.5 m^3) were matched simultaneously to the NT values [21]. To achieve this goal, a medicinal white oil was added as a third solvent to the GC. The light yield of the GC is optimized for homogeneous detector response using Monte Carlo simulations. To avoid mechanical stress on the detector vessels the densities of all four detector liquids were matched at the detector temperature of about 15°C to $0.804 \pm 0.001 \text{ g/cm}^3$.

The attenuation lengths for wavelengths in the region of scintillator emission are well above the dimensions of

FIG. 2. Average target detector response evolution in time, as measured by the mean energy of the Gd-capture peak arising from interaction of spallation neutrons in the NT.

the corresponding vessels. Optical stability of the scintillators is demonstrated in Figure 2, where the stability of the peak energy of neutron captures on Gd is shown. The energy response of the detector was found to be stable within 1% over the data-taking period of about one year.

The absolute number of H nuclei (“proton number”) as well as the precision on its knowledge are crucial parameters. The error on the proton number is minimized by using well defined and pure chemicals in combination with a precise knowledge of the weights of each chemical added in the scintillator production. The amount of NT scintillator was determined after thermalization by a weight measurement with a precision of 0.04%. The hydrogen fraction in the NT is 13.6% by weight, known with 0.3% relative precision. This error includes the uncertainties originating from the weights of the scintillator ingredients. In addition, the error takes into account the knowledge of the hydrogen content of not fully defined impurities in the chemicals which are on the per mil level for the main components [16].

A mixture of solvents was used in all detector volumes to allow for density matching. The 110 m³ of buffer liquid contain a medicinal white oil (53% by volume) and an n-alkane mixture (47% by volume). This liquid was optimized for transparency and low aromaticity to minimize scintillation light production in the buffer. The veto volume is filled with 90 m³ of liquid scintillator, a mixture of linear alkyl benzene (LAB) and n-alkanes, with 2 g/l PPO as fluor and 20 mg/l bis-MSB as secondary wavelength shifter.

D. ID Photomultiplier Tubes

The inner detector uses 390 Hamamatsu R7081 10-inch PMTs [22] to view the target volume. The glass is a low background type, contributing only a few Hz of singles rate in the detector. The PMTs are operated with a

gain of 10^7 at the PMT anode. They are submerged in a paraffin oil buffer liquid. The base circuit is enclosed in a transparent epoxy resin. Some PMTs are observed to generate light flashes from their base circuit through the epoxy resin, causing false triggers. HV for the 14 worst PMTs was turned off. Since the signal pattern is different from that of the neutrino signal, the false events are safely removed from the neutrino sample as described in Section IV D. The 800 PMTs for both this and an eventual near detector were characterized carefully [11, 12, 23]. The following characteristics were measured: for one photoelectron signals, the ratio of the one photoelectron peak to the valley between that peak and the pedestal was 4, with 1/4 photoelectron thresholds; the quantum efficiency $\times$ collection efficiency (efficiency that photoelectrons produced in the cathode are collected by the first dynode) was 23%; transit time spread was 3 ns (FWHM); the afterpulse probability was in average 2.7%; the charge output was linear up to 300 photoelectrons per PMT; dark hit rate was approximately 2 kHz measured 20 hours after turning on the HV. Each PMT is shielded by a mu-metal cylinder to suppress effects from the gamma shield and the earth’s magnetic field [13] and is equipped with an angle-adjustable mounting jig. The PMTs are angled to collect light more uniformly from the detector.

E. The Inner Veto

The IV is a cylindrical stainless steel vessel (radius 3.3 m and height 6.8 m) surrounding the ID and optically separated by the buffer tank. It shields the ID with a 50 cm thick layer of liquid scintillator against external radioactivity and spallation neutrons created by cosmic muons. At the same time it acts as an active detector identifying cosmic muons crossing it. The design of the IV was optimized by the use of a MC simulation [24], where the emphasis was on a high number of detected photoelectrons (PE) per MeV deposited in the IV volume and on a high efficiency in rejecting muons and correlated background events produced by them. The resulting configuration of the IV consists of 78 PMTs, divided into three parts: the top has 24 PMTs, the side walls have 12 PMTs at the mid way point and the bottom has 42 PMTs. The 78 8-inch PMTs (Hamamatsu R 1408), which were previously used in the IMB and Super-Kamiokande experiments, were tested and modified for use in Double Chooz [25]. Each IV PMT and its base are contained in a stainless steel encapsulation, with a transparent PET window at the front end. The capsules are filled with mineral oil to match the optical properties of the surrounding scintillator. All surfaces of the IV are painted with highly reflective white coating (AR100/CLX coating from MaxPerles [26]), the side walls of the buffer vessel are covered with reflective VM2000 sheets. Using the OV, the muon rejection efficiency was found to be larger than 99.99 % for muons

crossing the IV volume.

F. Electronics and Data Acquisition

The full readout and data acquisition (DAQ) for both the ID and the IV detectors are depicted in Figure 3. The functional principle is that digitization of PMT signals (see Section IID) is done by flash-ADC electronics. As shown in Figure 3, from left to right, the electronics elements are the High Voltage (HV) splitter, the HV supply, the Front-End electronics (FEE), the Trigger system [27] and the flash-ADC digitizing electronics [28, 29] (ν -FADC). Each PMT has a single cable for both PMT signal (5 mV per PE) and HV (~ 1.3 kV). A custom made HV-splitter circuit decouples both components. The HV is provided by CAEN-A1535P [30] supplies. PMT signals are optimized (amplified, clipped, baseline restored and coherent noise filtered) by the FEE for digitization. The FEE also delivers sum signals, whose amplitude is proportional to charge, that are fed into a custom trigger system. The circuit generating the sum signal subtracts the input amplitude after about 100 ns. This capability allows the trigger input signals to suffer from minimal overshoot that can lead to trigger dead-time. This same feature works as a high-pass filter: slow signals (frequency $\lesssim 1$ MHz) cannot cause a trigger. The ID PMTs are separated into two ID super-groups at the trigger level, uniformly distributed across the volume. Either super-group can cause a trigger of the ID based on energy and sub-group multiplicity information. The ID triggers at energies about 350 keV. The trigger efficiency is 100.0% above the analysis threshold 0.7 MeV with negligible uncertainty. Both energy and sub-group multiplicity information are used to cause IV triggers. The IV triggers at ~ 10 MeV which corresponds to 8 cm of a minimum ionizing muon track. The ν -FADC system relies on 64 CAEN-Vx1721(VME64x) [30] waveform digitizers. Each card has 8 channel with 8-bit flash-ADC (FADC) at 500 MS/s. Each channel holds up to 1024 4 μ s waveforms without readout. When triggered, the 256 ns waveform is recorded, containing $> 90\%$ of the scintillation light emitted. Up to ~ 3 MeV, a single-PE is deposited per channel, each having ~ 40 mV amplitude corresponding to around 10 samples per PE. FADC amplitude saturation leads to some degree of non-linearity for > 100 MeV energies. Above 500 MeV, up to a 40% non-linearity has been estimated.

The FADC baselines are observed to be stable, showing variations below 1 ADC. After power-cycling, small (sub-mV) DC shifts in the baseline are observed. Due to under-sampling of the baseline, these shifts can cause a bias in the reconstructed charge estimation. This bias manifests itself as an effective non-linearity for signals below 2 PEs and has been thoroughly studied, measured and calibrated out, as described in Section Section IV E.

All systems (trigger, ID and IV) are readout by the same DAQ upon any trigger of either the ID or IV. The

FIG. 3. Block diagram of the Double Chooz readout and DAQ systems.

system is deadtime free, as demonstrated by two monitor systems running at 2 Hz. The dead time monitor waveforms are, in addition, used to randomly sample the detector providing extra baseline monitoring, background and dark-current information.

G. The Outer Veto

The OV is installed above the ID, IV and 15 cm of shielding steel. A lower outer veto is mounted directly above the shielding and provides (x, y) coordinate for muons passing through a $13 \text{ m} \times 7 \text{ m}$ area centered on the chimney; a $110 \text{ cm} \times 30 \text{ cm}$ region around the chimney is left open. The lower outer veto has been installed for 68.9% of the data presented here, and is used to help reduce background levels quoted in [7]. An upper outer veto, again measuring (x, y) coordinates, has been mounted above the chimney and glove box used for source insertion, to cover this area. The upper outer veto was not present for this analysis.

The outer veto is assembled from modules containing 64 scintillator strips, each $5 \text{ cm} \times 1 \text{ cm} \times 320 \text{ cm}$ or 360 cm . Each strip was extruded with a hole running through its length, through which a 1.5 mm diameter wavelength-shifting fiber was threaded. Modules are built out of two superimposed 32-strip layers with the top layer offset by 2.5 cm from the bottom layer. The 64 fibers are coupled at one end to a Hamamatsu H8804 multi-anode photomultiplier tube (M64); the other fiber ends are mirrored. The OV modules are positioned over the inner detector in two layers, one with strips oriented in the x direction and one in the y direction. Each M64 is connected to a custom front-end board with a MAROC2 ASIC [31] and an FPGA. The MAROC2 allows adjustment of the electronic gain of each of the 64 channels, which is needed to correct for the factor of 2 pixel-to-pixel gain variation in the M64. Signals that exceed a common threshold are sent to a multiplexed 12-bit ADC, providing charge information for hit strips.

H. Calibration Systems

The experiment is calibrated using light sources, radioactive (point-like) sources, and cosmic rays.

A multi-wavelength LED–fiber system (LI) is used to inject light into the inner detector and the inner veto from a set of fixed points. The optical fibers of the LI are routed inside the detector and the fiber ends are attached to the PMT covers. Some of the injection points are equipped with diffuser plates to widely illuminate the detector. The other ends of the fibers are connected to blue and UV LEDs (385, 425 and 470 nm wavelengths for the ID, and 365 and 475 nm for the IV) whose flash rate, light intensity and pulse width are controlled remotely. Data are taken with the LI systems regularly. The LI data are used to measure the PMT and readout electronics gains and the time offsets and to monitor the stability of those gains and offsets.

Radio-isotopes ^{137}Cs , ^{68}Ge , ^{60}Co , and ^{252}Cf , sealed in miniature capsules, have been deployed in the NT and GC. The visible energy response is measured with a 0.662 MeV gamma (Cs-137), 2×0.511 MeV annihilation gammas (Ge-68), which also corresponds to the threshold for inverse beta decay, the combination of 1.173 MeV and 1.333 MeV gammas (Co-60), and the 2.223 MeV gamma from neutron capture on hydrogen (Cf-252). The detector response to neutrons is calibrated using ^{252}Cf . Source rates are at the level of 50 Bq.

Deployments in the NT are realized by lowering the sources from a glove box at the detector top through the detector chimney. A motorized pulley-and-weight system, operated from a glove box, is used to position sources at positions along the target symmetry axis. The range of deployments is from 1 cm above the NT bottom up to the chimney; the positions of the source are known within 1 mm. In the GC, the source is attached to a motor-driven wire and guided through a rigid hermetic looped tube (GT). The sources are inserted in the GT near the chimney top. The loop traverses interior regions of the GC and passes near boundaries with the NT and the buffer. The position of the source along the loop is known to 1 cm, and in the NT boundary region, the perpendicular distance between the source and the target wall is known within 2 mm. The materials of the source capsules and deployment systems in the NT and GC are modeled by the detector simulation.

Cosmic rays are analyzed to identify stopping muons, spallation neutrons, and cosmogenic radioactive isotopes. Several thousand spallation neutrons per day are captured on hydrogen and gadolinium in the ID.

The use of the calibration data for issues of energy uniformity, stability, non-linearity and absolute calibration is described in Section IV E. The neutron detection efficiency from ^{252}Cf is described in Section V F. Good control of uncertainties on detection efficiency is essential for sensitivity to neutrino disappearance with a single detector. The detailed calibration data allow a precise energy-shape fit to the prompt neutrino candidates for

the most sensitive extraction of θ_{13} .

III. REACTOR AND DETECTOR MODELS

A. Thermal Power

Double Chooz’s sources of antineutrinos are the reactor cores B1 and B2 at the Électricité de France (EDF) Centrale Nucléaire de Chooz. Antineutrinos are produced in nuclear reactors by the β -decay of the fission products. Four main isotopes, ^{235}U , ^{239}Pu , ^{238}U , and ^{241}Pu , provide >99.7% of the fissions and antineutrinos.

Chooz B1 and B2 are N4 type pressurized water reactor (PWR) cores, and as such are two of the most powerful cores in the world with nominal thermal power outputs of 4.25 GW_{th} each. The instantaneous thermal power of each reactor core P_{th}^R is provided by EDF as a fraction of the total power and is evaluated over time steps of <1 minute. The instantaneous thermal power is derived from the in-core instrumentation with the most important variable being the temperature of the water in the primary loop.

The in-core instrumentation calibration is tested weekly using the heat balance in the secondary loop, which is heated by the primary loop containing water heated by fissions. In the secondary loop, steam is generated to drive turbines. By using measurements of the heat flow in the secondary loop, the thermal power can be measured. This test is performed with the reactor running at full power. The uncertainty at lower power is therefore slightly larger. The in-core instrumentation is re-calibrated if it deviates by more than the uncertainty in the heat balance measurement.

Since the accuracy of the thermal power measurement determines the maximum power at which the core can operate, EDF has performed a detailed study of the uncertainty in this measurement [32–34]. The dominant uncertainty on the weekly heat balance at the secondary loops comes from the measurement of the water flow. At the nominal full power of 4250 MW the final uncertainty is 0.5% (1σ C.L.). Since the amount of data taken with one or two cores at intermediate power is small, this uncertainty is used for the mean power of both cores. This is smaller than the typical uncertainty for PWRs of 0.7% [35] and reflects optimizations in the pipe geometry of the secondary loop, as well as great care taken to understand the sensor uncertainties, including full-scale test stands for the most critical sensors.

B. Mean Cross Section per Fission

The mean cross section per fission is effectively a spectrum averaged cross section. It is given by

$$\langle \sigma_f \rangle = \sum_k \alpha_k \langle \sigma_f \rangle_k = \sum_k \alpha_k \int_0^\infty dE S_k(E) \sigma_{IBD}(E) \quad (1)$$

where α_k is the fractional fission rate of the k^{th} isotope ($k = {}^{235}\text{U}$, ${}^{239}\text{Pu}$, ${}^{238}\text{U}$, ${}^{241}\text{Pu}$), $S_k(E)$ is the reference spectrum of the k^{th} isotope and σ_{IBD} is the inverse beta decay cross section. The determinations of the α_k require the simulation of the reactor core (Section III C).

The antineutrino spectrum for each fission isotope is the result of the beta decays of many different fission products. For ${}^{235}\text{U}$, ${}^{239}\text{Pu}$, and ${}^{241}\text{Pu}$, the reference antineutrino spectra are derived from measurements of the β spectra at the ILL research reactor [36–38]. In the case of ${}^{238}\text{U}$, an ab initio calculation of the spectrum is used [39]. The conversion of the β spectra to antineutrino spectra has recently been improved by using more data on the many β transitions and higher order energy corrections [39, 40]. We use the conversion scheme of [40] including corrections for off-equilibrium effects [41]. The uncertainty on these spectra is energy dependent but is on the order of 3%. The new technique for the analysis of the β spectra has led to an overall change in the normalization of the $S_k(E)$ that, when applied to previous reactor antineutrino experiments, results in measurements that are lower than predictions for experiments at short baselines [41].

C. Fission Rate Computation

The fractional fission rates α_k of each isotope are needed in order to calculate the mean cross section per fission of (Equation 1). They are also required for the calculation of the mean energy released per fission for reactor R :

$$\langle E_f \rangle_R = \sum_k \alpha_k \langle E_f \rangle_k. \quad (2)$$

The mean energies released per fission per isotope $\langle E_f \rangle_k$ are summarized in Table I. The thermal power one would calculate given a fission is relatively insensitive to the specific fuel composition since the $\langle E_f \rangle_k$ differ by <6%; however, the difference in the detected number of antineutrinos is amplified by the dependence of the norm and mean energy of $S_k(E)$ on the fissioning isotope. For this reason, much effort has been expended in developing simulations of the reactor cores to accurately model the evolution of the α_k .

Double Chooz has chosen two complementary codes for modeling of the reactor cores: MURE and DRAGON [42–45]. MURE is a 3D full core simulation which uses Monte Carlo techniques to model the neutron transport

in the core. DRAGON is a 2D simulation which models the individual fuel assemblies. Using some approximations, it solves the neutron transport equation in the core. These two codes provide the needed flexibility to extract fission rates and their uncertainties. These codes were benchmarked against data from the Takahama-3 reactor and were found to be consistent with other codes commonly used in the reactor industry for reactor modeling within the uncertainty in the Takahama data [46].

The construction of the reactor model requires detailed information on the geometry and materials comprising the core. The Chooz cores are comprised of 205 fuel assemblies. For every reactor fuel cycle, approximately one year in duration, one third of the assemblies are replaced with assemblies containing fresh fuel. The other two thirds of the assemblies are redistributed to obtain a homogeneous neutron flux across the core. The Chooz reactor cores contain four assembly types that differ mainly in their initial ${}^{235}\text{U}$ enrichment. These enrichments are 1.8%, 3.4% and 4%.

The data set presented here spans fuel cycle 12 for core B2 and cycle 12 and the beginning of cycle 13 for B1. EDF provides Double Chooz with the locations and initial burnup of each assembly. Based on these maps, a full core simulation was constructed using MURE for each cycle. In addition, the beginning-of-fuel-cycle composition needs to be determined based on the burnup of each assembly. To accomplish this, an assembly-level reference simulation is run using both MURE and DRAGON for each of the four fuel assembly types. The results of the reference simulations are compared to EDF's own simulation code APOLLO2-F from which the burnup values are derived. The uncertainty due to the simulation technique is evaluated by comparing the DRAGON and MURE results for the reference simulation leading to a small 0.2% systematic uncertainty in the fission rate fractions α_k .

Once the initial fuel composition of the assemblies is known, MURE is used to model the evolution of the full core in time steps of 6 to 48 hours, depending on the operating conditions of the reactor. The results from each simulation time step are written to a database. This allows the α_k 's, and therefore the predicted antineutrino flux, to be calculated. The results averaged over the current data set are shown in Table I.

The systematic uncertainties on the α_k 's are determined by varying the inputs and observing their effect on the fission rate relative to the nominal simulation. The uncertainties considered are those due to the thermal power, boron concentration, moderator temperature and density, initial burnup error, control rod positions, choice of nuclear databases, choice of the energies released per fission, and statistical error of the MURE Monte Carlo. The systematic errors associated with each input are considered independently and the uncertainties propagated quadratically. The correlation coefficients among isotopic fission rates due to the thermal power constraint are also computed, and a covariance matrix is constructed with these contributions in order to properly account for those

TABLE I. Mean energy released per fission $\langle E_f \rangle_k$ from [47] and fractional fission rate $\langle \alpha_k \rangle$ of the isotope k for this data.

Isotope	$\langle E_f \rangle_k$ (MeV)	$\langle \alpha_k \rangle$
^{235}U	201.92 ± 0.46	0.496 ± 0.016
^{239}Pu	209.99 ± 0.60	0.351 ± 0.013
^{238}U	205.52 ± 0.96	0.087 ± 0.006
^{241}Pu	213.60 ± 0.65	0.066 ± 0.007

correlations. The uncertainties in the α_k 's are listed in Table I. The two largest contributions come from the moderator density and control rod positions.

D. Bugey4 Normalization and Antineutrino Rate Calculation

In the current, far-only, phase of Double Chooz, the rather large uncertainties in the reference spectra of Section III B limited our sensitivity to θ_{13} . To mitigate this effect, the normalization of the cross section per fission for each reactor is “anchored” to the Bugey4 rate measurement at 15 m [48]:

$$\langle \sigma_f \rangle_R = \langle \sigma_f \rangle^{\text{Bugey}} + \sum_k (\alpha_k^R - \alpha_k^{\text{Bugey}}) \langle \sigma_f \rangle_k. \quad (3)$$

where R stands for each reactor. The second term corrects for the difference in fuel composition between Bugey4 and each of the Chooz cores. This treatment takes advantage of the high accuracy of the Bugey4 anchor point (1.4%) and suppresses the dependence on the predicted $\langle \sigma_f \rangle_R$. This is due to the smallness of the correction term $(\alpha_k^R - \alpha_k^{\text{Bugey}})$. At the same time, the analysis becomes insensitive to possible oscillations at shorter baselines due to heavy $\Delta m^2 \sim 1 \text{ eV}^2$ sterile neutrinos.

The expected number of antineutrinos with no oscillation in the i^{th} energy bin with the Bugey4 anchor point becomes:

$$N_i^{\text{exp}, R} = \frac{\epsilon N_p}{4\pi} \frac{1}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \times \left(\frac{\langle \sigma_f \rangle_R}{(\sum_k \alpha_k^R \langle \sigma_f \rangle_k)} \sum_k \alpha_k^R \langle \sigma_f \rangle_k^i \right) \quad (4)$$

where ϵ is the detection efficiency, N_p is the number of protons in the target, L_R is the distance to the center of each reactor, and P_{th}^R is the thermal power. The variable $\langle E_f \rangle_R$ is the mean energy released per fission defined in Equation 2, while $\langle \sigma_f \rangle_R$ is the mean cross section per fission defined in Equation 3. The three variables P_{th}^R , $\langle E_f \rangle_R$ and $\langle \sigma_f \rangle_R$ are time dependent with $\langle E_f \rangle_R$ and $\langle \sigma_f \rangle_R$ depending on the evolution of the fuel composition in the reactor and P_{th}^R depending on the operation of the reactor.

A covariance matrix $M_{ij}^{\text{exp}} = \delta N_i^{\text{exp}} \delta N_j^{\text{exp}}$ is constructed using the uncertainties listed in Table II. This

TABLE II. The uncertainties in the antineutrino prediction. All uncertainties are assumed to be correlated between the two reactor cores. They are assumed to be normalization and energy (rate and shape) unless noted as normalization only.

Source	Normalization Only	Uncertainty [%]
P_{th}	yes	0.5
$\langle \sigma_f \rangle^{\text{Bugey}}$	yes	1.4
$S_k(E) \sigma_{IBD}(E_\nu^{\text{true}})$	no	0.2
$\langle E_f \rangle$	no	0.2
L_R	yes	<0.1
α_k^R	no	0.9
Total		1.8

matrix is constructed in terms of real energy and is converted into reconstructed energy by running multiple simulations drawn from a Cholesky decomposition of M_{ij}^{exp} . For these simulations, the full detector Monte Carlo described below is used. The use of Equation 4 to construct the covariance matrix allows time and spectral information to propagate to the final analysis.

The IBD cross section used is the simplified form from Vogel and Beacom [49]:

$$\sigma_{IBD}(E_\nu^{\text{true}}) = E_{e+} K \sqrt{E_{e+}^2 - m_e^2} \quad (5)$$

where

$$E_{e+} = \frac{1}{2} \left(\sqrt{m_n^2 - 4m_p \left(-E_\nu + \Delta + \frac{\Delta^2 - m_e^2}{2m_p} \right)} - m_n \right) \quad (6)$$

and m_e and E_{e+} are the positron mass and energy. The variables m_n and m_p are the masses of the neutron and proton with $\Delta = m_n - m_p$. The constant K is inversely proportional to the neutron lifetime. We use the MAMBO-II measurement of the neutron lifetime [50] and find $K = 0.961 \times 10^{-43} \text{ cm}^2 \text{ MeV}^{-2}$.

E. Detector Model

We model the detector response using a detailed Geant4 [51] simulation with enhancements to the scintillation process, photocathode optical surface model, and thermal neutron model. Apart from these additions, the physics list is similar to Geant4's QGSP_BERT_HP reference physics list [52], without processes for high-mass hadrons. Our custom scintillation process implements detailed light waveforms, spectra, re-emission, and Birks-law [53] quenching. Our photocathode model is based on a standard mathematical model of a thin, semitransparent surface with absorption and refractive index [54], and also includes the collection efficiency for photoelectrons as a function of position of emission on the photocathode. Our custom neutron thermalization process implements molecular elastic scattering for neutrons under 4 eV and a

radiative capture model with improved final state gamma modeling.

The simulation models the detector geometry to a fine level of detail, particularly with regard to the geometry of the phototubes and mu-metal shields and of all materials near the active volume such as tank walls and supports. The orientation and positions of the phototube assemblies were set using data from a photographic survey with sub-mm accuracy. The dimensions of the tank walls and supports were checked by experimenters during assembly and installation, and placement also verified by photographic survey.

Simulated IBD events are generated with run-by-run correspondence of MC to data, with fluxes and rates calculated as described in Section III D. Radioactive decays in calibration sources and spallation products were simulated using detailed models of nuclear levels, taking into account branching ratios and correct spectra for transitions [55].

Optical parameters used in the detector model are based on detailed measurements made by the collaboration. The relative light yield of the NT compared to the GC was measured using a Compton backscatter peak method in order to select scattered electrons with fixed energy [21]. Tuning of the absolute and relative light yield in the simulation was done with calibration data. The scintillator emission spectrum was measured using a Cary Eclipse fluorometer [56]. The photon emission time probabilities used in the simulation are obtained with a dedicated laboratory setup [16]. For the ionization quenching treatment in our MC, the light output of the scintillators after excitation by electrons [57] and alpha particles [58] of different energies was measured. The non-linearity in light production in the simulation has been adjusted to match these data. The attenuation and re-emission probabilities of each of the scintillator components in the relevant wavelength range are implemented in the MC. The fine-tuning of the total attenuation was made using measurements of the complete scintillators [16]. Other measured optical properties include reflectivities of various detector surfaces and indices of refraction of detector materials.

F. Readout System Simulation

The Readout System Simulation (RoSS) accounts for the response of elements associated with detector readout, such as from the PMTs, FEE, FADCs, trigger system and DAQ. The simulation relies on the measured probability distribution function (PDF) to empirically characterize the response to each single PE as measured by the full readout channel. The Geant4-based simulation calculates the time at which each PE strikes the photocathode of each PMT. RoSS converts this time-per-PE into an equivalent waveform as digitized by FADCs. A dedicated setup was built to measure most of the necessary PDFs as well as to tune the design of the full

readout chain. Channel-to-channel variations, such as gains, baselines, noise, single PE widths, etc., are taken into consideration, to accurately predict dispersion effects. This capability allows the simulation to exhibit non-linearity effects as observed in the data, as described in Section II F. After calibration, the MC and data energies agree within 1%. About 25% of the width of the calibrated H-capture (2.2 MeV γ line) results from readout effects; i.e., effects beyond photon-statistics fluctuations.

G. Monte Carlo $\bar{\nu}_e$ Event Generation

A set of Monte Carlo $\bar{\nu}_e$ events representing the expected signal for the duration of physics data-taking is created based on the formalism of Equation 4. The calculated IBD rate is used to determine the rate of interactions. Parent fuel nuclide and neutrino energies are sampled from the calculated neutrino production ratios and corresponding spectra, yielding a properly normalized set of IBD-progenitor neutrinos.

Once generated, each event-progenitor neutrino is assigned a random creation point within the originating reactor core. The event is assigned a weighted-random interaction point within the detector based on proton density maps of the detector materials. In the center-of-mass frame of the $\nu - p$ interaction, a random positron direction is chosen, with the positron and neutron of the IBD event given appropriate momenta based on the neutrino energy and decay kinematics. These kinematic values are then boosted into the laboratory frame. The resulting positron and neutron momenta and originating vertex are then available as inputs to the Geant4 detector simulation. “Truth” information regarding the neutrino origin, baseline, and energy are propagated along with the event, for use later in the oscillation analysis.

IV. RECONSTRUCTION

A. Pulse Reconstruction

The pulse reconstruction provides the signal charge and time in each PMT. Pulser triggers are taken with a rate of 1 Hz in order to provide accurate information about the baseline for each of the 468 readout channels. The baseline mean (B_{mean}) and rms (B_{rms}) are computed using the full readout window (256 ns).

The integrated charge (q) is defined as the sum of digital counts in each waveform sample over the integration window, once the pedestal has been subtracted. The pedestal is computed as the integration of B_{mean} over the same window. In order to improve the charge resolution, the size of the integral window has been set to a 112 ns subsample of the readout one, based on the width of the single PE signals.

In order to find the pulses within the readout window, a dynamic window algorithm is used. The algo-

rithm searches for the 112 ns window which maximizes the integral. In the absence of an actual PE signal, this algorithm would reconstruct the largest noise fluctuation, leading to a bias in the charge reconstruction. To address this, we introduce two requirements: ≥ 2 ADC counts in the maximum bin, and $q > B_{rms} \times \sqrt{N_s}$, where N_s is the number of integrated waveform samples (56 for a 112 ns window). For each pulse reconstructed, the start time is computed as the time when the pulse reaches 20% of its maximum. This time is then corrected by the PMT-to-PMT offsets obtained with the LI system.

B. Vertex Reconstruction

Vertex reconstruction in Double Chooz is not used for event selection, but is used for event energy reconstruction. It is based on a maximum charge and time likelihood algorithm which utilizes all hit and no-hit information in the detector. Assuming the event to be a point-like source of light characterized by the set

$$\mathbf{X} = (x_0, y_0, z_0, t_0, \Phi) \quad (7)$$

where (x_0, y_0, z_0) is the event position in the detector, t_0 is the event time and Φ is the light intensity per unit solid angle (expressed in photons/sr), the amount of light and prompt arrival time at the i -th PMT can be predicted as

$$\mu_i = \Phi \epsilon_i \Omega_i A_i \quad (8)$$

and

$$t_i^{(pred)} = t_0 + \frac{r_i}{c_n} \quad (9)$$

respectively, where ϵ_i is the quantum efficiency of the PMT, Ω_i is the solid angle subtended by the PMT at a distance r_i from the event vertex, A_i is the light transmission amplitude, and c_n is the effective speed of light in the medium.

The event likelihood is defined as

$$\mathcal{L}(\mathbf{X}) = \prod_{q_i=0} f_q(0; \mu_i) \prod_{q_i>0} f_q(q_i; \mu_i) f_t(t_i; t_i^{(pred)}, \mu_i) \quad (10)$$

where the first product goes over the PMTs that have not been hit, while the second product goes over the remaining PMTs that have been hit (i.e., have a non-zero recorded charge q_i at the registered time t_i). $f_q(q_i; \mu_i)$ is the probability to measure a charge q_i given an expected charge μ_i , and $f_t(t_i; t_i^{(pred)}, \mu_i)$ is the probability to measure a time t_i given a prompt arrival time $t_i^{(pred)}$ and predicted charge μ_i . These are obtained from MC simulations and verified against the physics and calibration data. The task of the event reconstruction is to find the best possible set of event parameters $\mathbf{X}_{min}$ which maximizes the event likelihood $\mathcal{L}(\mathbf{X})$, or equivalently, mini-

mizes the negative log-likelihood function

$$F(\mathbf{X}) = -\ln \mathcal{L}(\mathbf{X}) = -\sum_i \ln f_q(q_i; \mathbf{X}) - \sum_{q_i>0} \ln f_t(t_i; \mathbf{X}) = F_q(\mathbf{X}) + F_t(\mathbf{X}). \quad (11)$$

Note that the event reconstruction can be performed using either one or both of the two terms in the expression above, F_q for a charge-only reconstruction, or F_t for a time-only reconstruction; utilizing both components enhances the accuracy and stability of the algorithm.

The performance of the Double Chooz reconstruction has been evaluated in situ using radioactive sources deployed at known positions along the z -axis in the target volume, and off-axis in the guide tubes. The sources are reconstructed with a spatial resolution of 32 cm for ^{137}Cs , 24 cm for ^{60}Co , and 22 cm for ^{68}Ge .

C. Muon tagging and reconstruction

Cosmic muons passing through the detector or the nearby rock induce backgrounds which are discussed in the next section. A through-going (stopping) muon typically deposits 160 MeV (80 MeV) in the IV which triggers above about 10 MeV. The IV trigger rate is 46 s^{-1} . All muons in the ID are tagged by the IV except some stopping muons which enter the chimney. Muons which stop in the ID and their resulting Michel e can be identified by demanding a large energy deposition (roughly a few tens of MeV) in the ID. An event is tagged as a muon if there is > 5 MeV in the IV or > 30 MeV in the ID.

Several tracking algorithms have been developed to reconstruct these muons. IV reconstruction is based on a maximum likelihood algorithm utilizing the arrival times of the earliest photons to hit each PMT, while ID reconstruction utilizes the spatial pattern of hit times. The forward wavefront of scintillation light from a relativistic track propagates at the Cerenkov angle, thus allowing the same algorithm to be used for tracks in the NT, GC, and non-scintillating buffer. Using MC and the OV as reference, the lateral resolution at the detector center has been determined to be 35 cm for ID and 60 cm for IV muons.

D. Light Noise Rejection

The background known as *light noise* is caused by a sporadic spontaneous flashes of some PMT bases. The characteristic signature is light mainly localized to one PMT base and spread out in time among the other PMTs after many reflections from the detector surfaces. This background can be discriminated from physics events based on the fact that the detected light is spread less homogeneously across the detector for light noise events. Light noise is rejected by demanding both a small value of

$Q_{\max}/Q_{\text{tot}}$, where $Q_{\max}$ is the maximum charge recorded by a single PMT and Q_{tot} is the total ID charge collected in a trigger, and large values of $\text{rms}(t_{\text{start}})$, which is the standard deviation of the distribution of the start time (t_{start}) of the first pulse on each PMT.

E. Energy Reconstruction

The visible energy (E_{vis}) provides the absolute calorimetric estimation of the energy deposited per trigger. E_{vis} is a function of the calibrated PE (total number of photoelectrons):

$$E_{\text{vis}} = PE^m(\rho, z, t) \times f_u^m(\rho, z) \times f_s^m(t) \times f_{\text{MeV}}^m, \quad (12)$$

where $PE = \sum_i pe_i = \sum_i q_i/\text{gain}_i(q_i)$. Coordinates in the detector are ρ and z , t is time, m refers to data or Monte Carlo (MC) and i refers to each good channel. The correction factors f_u , f_s and f_{MeV} correspond, respectively, to the spatial uniformity, time stability and PE/MeV calibrations. Four stages of calibration are carried out to render E_{vis} linear, independent of time and position, and consistent between data and MC. Both the MC and data are subjected to the same stages of calibration.

The sum over all good channels of the reconstructed raw charge (q_i , see Section IV A) from the digitized waveforms is the basis of the energy estimation. Good channels are those identified and tagged as well behaved by fast online analysis based on waveform information. Only a very few channels are sporadically not good and are, thus, excluded from the calorimetric estimation. The limited sampling of the waveform baseline estimation can be biased [28] leading to a non-linearity at about 1 PE charge equivalent. Figure 4 shows the effect for a representative channel. A similar curve is used to calibrate the MC. The PE calibrated charge (pe_i) is defined as $pe_i = q_i/\text{gain}_i(q_i)$. One $\text{gain}_i(q_i)$ curve is generated upon each power-cycle episode. Due to the average light level ($\sim 230 \text{ } PE/\text{MeV}$), the non-linear bias of the single- PE calibration can have up to a 10% effect for energies below 3 MeV, if not corrected.

The PE response is position dependent for both MC and data. Calibration maps were created such that any PE response for any event located at any position (ρ, z) can be converted into its response as if measured at the center of the detector ($\rho = 0, z = 0$): $PE_{\odot}^m = PE^m(\rho, z) \times f_u^m(\rho, z)$. The calibration map's correction for each point is labeled $f_u^m(\rho, z)$. Independent uniformity calibration maps $f_u^m(\rho, z)$ are created for data and MC, such that the uniformity calibration serves to minimize any possible difference in position dependence of the data with respect to MC. The capture peak on H (2.223 MeV) of neutrons from spallation and antineutrino interactions provides a precise and copious calibration source to characterize the response non-uniformity over the full volume (both NT and GC). The calibration map for data is shown in Figure 5. A similar map

FIG. 4. Demonstration of the linear PE calibration for one channel. The gain versus charge is shown. The dashed line highlights the constant component (linear behavior) of the gain observed at large charges. The calibration parametrizes this curve to correct the non-linear component (deviation from constant) of the gain, making the PE corrected energy scale linear to within 2%.

FIG. 5. Detector calibration map, in cylindrical coordinates (ρ, z), as sampled with spallation neutrons capturing in H across the ID. Response variations are quantified as the fractional response with respect to the detector center. Largest deviation in NT are up to 5%. A similar map is constructed with MC for calibration of its slightly different response uniformity pattern.

was measured and applied to MC. A 2D-interpolation method was developed to provide a smooth application of the calibration map at any point (ρ, z).

The detector response stability was found to vary in time due to two effects, which are accounted for and corrected by the term $f_s^m(t)$. First, the detector response can change due to variations in readout gain or scintillator response. This effect has been measured as a +2.2% monotonic increase over 1 year using the response of the spallation neutrons capturing on Gd within the NT, shown in Figure 2. Second, a few readout chan-

FIG. 6. Stability of the reconstructed energy as sampled by the evolution in response of the spallation neutron H-capture after stability calibration. The observed steps correspond to power-cycle periods. The systematic uncertainty on the energy stability is estimated at 0.61%.

TABLE III. Energy scale systematic errors.

	Error (%)
Relative Non-Uniformity	0.43
Relative Instability	0.61
Relative Non-Linearity	0.85
Total	1.13

nels varying over time are excluded from the calorimetry sum, and the average overall response decreases by 0.3% per channel excluded. The MC is stable, so this correction is applied only to data. The stability calibration is relative to a specific reference time t_0 . Therefore, any response $PE_{\odot}(t)$ is converted to the equivalent response at t_0 , as $PE_{\odot}^m(t) = PE_{\odot}^m(t) \times f_s^m(t)$. The t_0 was defined as the day of the first Cf source deployment, during August 2011. The remaining instability after calibration is shown in Figure 6, as sampled with H-capture from spallation neutrons, and is used for the stability systematic uncertainty estimation.

The number $PE_{\odot t_0}$ per MeV is determined by an absolute energy calibration independently, for the data and MC. The response in $PE_{\odot t_0}$ for H-capture as deployed in the center of the NT is used for the absolute energy scale. The absolute energy scales are found to be $229.9 PE_{\odot t_0}/\text{MeV}$ and $227.7 PE_{\odot t_0}/\text{MeV}$, respectively, for the data and MC, demonstrating agreement within 1% prior to this calibration stage.

Discrepancies in response between the MC and data, after calibration, are used to estimate these uncertainties within the prompt energy range and the NT volume. Table III summarizes the systematic uncertainty in terms of the remaining non-uniformity, instability and non-linearity. The relative non-uniformity systematic uncertainty was estimated from the calibration maps using neutrons capturing on Gd, after full calibration. The rms deviation of the relative difference between the data and MC calibration maps is used as the estimator of

the non-uniformity systematic uncertainty, and is 0.43%. This result is consistent with the analysis of all calibration sources along the z -axis (NT) and GT (GC). The relative instability systematic error, discussed above, is 0.61%. Responses are equalized at 2.223 MeV, but small data/MC discrepancies in the absolute energy scale can still arise from the relative non-linearity across the prompt energy spectrum. This possibility was explored by using all calibration sources in the energy range 0.7 – 8 MeV with deployments along the z -axis and GT. Some relative non-linearity was observed ($< 0.2\%/ \text{MeV}$) but the pattern diminished when integrated over the full volume. A 0.85% variation consistent with this non-linearity was measured with the z -axis calibration system, and this is used as the systematic error for relative non-linearity in Table III. Consistent results were obtained when sampling with the same sources along the GT.

V. NEUTRINO DATA ANALYSIS

A. $\bar{\nu}_e$ Candidate Selection

The $\bar{\nu}_e$ candidate selection procedure starts in a similar way as [7]. Events with an energy below 0.5 MeV, where the trigger efficiency is not 100%, or identified as light noise ($Q_{\text{max}}/Q_{\text{tot}} > 0.09$ or $\text{rms}(t_{\text{start}}) > 40$ ns) are discarded. Triggers within a 1 ms window following a tagged muon are also rejected (see Section IV C), in order to reduce the correlated and cosmogenic backgrounds. The effective veto time is 4.4% of the total run time. Defining $\Delta T \equiv t_{\text{delayed}} - t_{\text{prompt}}$, further selection consists of 4 cuts:

1. time difference between consecutive triggers (prompt and delayed): $2 \mu\text{s} < \Delta T < 100 \mu\text{s}$, as shown in Figure 7, where the lower cut reduces correlated backgrounds and the upper cut is determined by the approximately 30 μs capture time on Gd;
2. prompt trigger: $0.7 \text{ MeV} < E_{\text{prompt}} < 12.2 \text{ MeV}$, as illustrated in Figure 8;
3. delayed trigger: $6.0 \text{ MeV} < E_{\text{delayed}} < 12.0 \text{ MeV}$ (Figure 8) and $Q_{\text{max}}/Q_{\text{tot}} < 0.055$;
4. multiplicity: no additional triggers from 100 μs preceding the prompt signal to 400 μs after it, with the goal of reducing the correlated background.

The IBD efficiencies for these cuts are listed in Table IV.

A preliminary sample of 9021 candidates is obtained by applying selections (1–4). In order to reduce the background contamination in the sample, candidates are rejected according to two extra cuts not used in [7]. First, candidates within a 0.5 s window after a high energy muon crossing the ID ($E_{\mu} > 600 \text{ MeV}$) are tagged as cosmogenic isotope events and rejected, increasing the

Cut	Efficiency %
E_{prompt}	100.0 ± 0.0
E_{delayed}	94.1 ± 0.6
ΔT	96.2 ± 0.5
Multiplicity	99.5 ± 0.0
Muon veto	90.8 ± 0.0
Outer Veto	99.9 ± 0.0

TABLE IV. Cuts used in the event selection and their efficiency for IBD events. The OV was working for the last 68.9% of the data.

FIG. 7. Time difference between prompt and delayed triggers. Black dots and solid histogram show data and MC results, respectively.

effective veto time to 9.2%. Second, candidates whose prompt signal is coincident with an OV trigger are also excluded as correlated background. Applying the above vetoes yields 8249 candidates or a rate of 36.2 ± 0.4 events/day, uniformly distributed within the target, for an analysis livetime of 227.93 days. This rate is lower than the one presented in [7] due to a longer data taking period with one reactor being off, as well as to the new cuts reducing the background contamination. Following the same selection procedure on the $\bar{\nu}_e$ MC sample yields 8439.6 expected events in the absence of oscillation.

B. Accidental Background

The main source of accidental coincidences is the random association of a prompt trigger from natural radioactivity and a later neutron-like candidate. This background is estimated by applying the neutrino selection cuts described in Section V A but using coincidence windows shifted by 1 s in order to remove correlations in the time scale of n-captures in H and Gd. The statistics of

FIG. 8. Delayed energy versus prompt energy for time-correlated triggers. Vertical and horizontal dashed lines show the cuts applied for $\bar{\nu}_e$ candidates selection.

the sample is enhanced by using 198 windows each shifted from the previous one by $500 \mu\text{s}$. The radioactivity rate between 0.7 and 12.2 MeV is 8.2 s^{-1} , while the singles rate in 6 - 12 MeV energy region is 18 h^{-1} . Both rates are quite stable along the data taking period. Finally, the accidental background rate is found to be 0.261 ± 0.002 events per day. The reproducibility of our result and any possible systematic effect are studied by repeating the procedure 30 times, i.e., taking 30 times 198 consecutive time windows. The dispersion of these 30 measurements is consistent with only statistical error, so, no systematic deviation is found.

Figure 9 shows the accidental prompt spectrum and the energy distribution for natural radioactivity scaled to the number of accidental events; the agreement is excellent. The distribution is peaked at low energies below 3 MeV. The remaining light noise is included in the accidental background sample. Using the correlation between both variables $Q_{\text{max}}/Q_{\text{tot}}$ and $\text{rms}(t_{\text{start}})$, its contribution to the accidental sample is estimated to be lower than 1%.

C. Cosmogenic Isotopes Background

The radioisotopes ^8He and ^9Li are products of spallation processes on ^{12}C induced by cosmic muons crossing the scintillator volume. The βn -decays of these isotopes constitute a background for the antineutrino search. βn -emitters can be identified from the time- and space-correlation to their parent muon. Due to their relatively long lifetimes (^9Li : $\tau = 257 \text{ ms}$, ^8He : $\tau = 172 \text{ ms}$), an event-by-event discrimination is not possible. For the

FIG. 9. The accidental prompt spectrum (black circles) superimposed to the radioactivity energy distribution measured in Double Chooz scaled to the same number of entries (red line).

muon rates in our detector, vetoing for several isotope lifetimes after each muon would lead to an unacceptably large loss in exposure. Instead, the rate is determined by an exponential fit to the $\Delta t_{\mu\nu} \equiv t_\mu - t_\nu$ profile of all possible muon-IBD candidate-pairs.

The analysis is performed for three visible energy E_μ^{vis} ranges that characterize subsamples of parent muons by their energy deposition, not corrected for energy non-linearities, in the ID:

1. Showering muons crossing the target value are selected by $E_\mu^{vis} > 600$ MeV and feature an increased probability to produce cosmogenic isotopes. The $\Delta t_{\mu\nu}$ -fit returns a precise result of 0.95 ± 0.11 events/day for the βn -emitter rate.
2. In the E_μ^{vis} range from 275 to 600 MeV, muons crossing GC and target still give a sizable contribution to isotope production of 1.08 ± 0.44 events/day. To obtain this result from a $\Delta t_{\mu\nu}$ fit, the sample of muon-IBD pairs has to be cleaned by a spatial cut on the distance of closest approach from the muon to the IBD candidate of $d_{\mu\nu} < 80$ cm to remove the majority of uncorrelated pairs. The corresponding cut efficiency is determined from the lateral distance profile obtained for $E_\mu^{vis} > 600$ MeV. The approach is validated by a comparative study of cosmic neutrons that show an almost congruent profile with very little dependence on E_μ^{vis} above 275 MeV.
3. The Cut $E_\mu^{vis} < 275$ MeV selects muons crossing only the buffer volume or the rim of the GC. For this sample, no production of βn -emitters inside the target volume is observed. An upper limit of < 0.3 events/day can be established based on a $\Delta t_{\mu\nu}$ fit for $d_{\mu\nu} < 80$ cm. Again, the lateral distribution of cosmic neutrons has been used for determining the cut efficiency.

FIG. 10. The prompt β spectrum of the βn -emitters ^8He and ^9Li from data (black squares) and Monte Carlo (red line), assuming ^9Li is the dominant contribution.

The overall rate of βn -decays found is $2.05^{+0.62}_{-0.52}$ events/day. The result of a similar analysis based on the IV muon tracking agrees within the uncertainty.

Accidental coincidences containing the β -decay of the isotope ^{12}B either as prompt or as delayed event feature a time correlation to the parent muons producing the ^{12}B . In the $\Delta t_{\mu\nu}$ profile, these events are represented by a decay function with $\tau(^{12}\text{B}) = 29$ ms. However, these events were removed very efficiently from the data set used for ^9Li analysis by imposing a maximum distance cut of 90 cm between prompt and delayed events, introducing a negligible inefficiency of $\sim 1\%$.

The correlation of a cosmogenic isotope to the showering muons has been exploited to impose a partial veto of this background for the final fit analysis. Vetoing all IBD candidates within 0.5 s following a muon of $E_\mu^{vis} > 600$ MeV, 0.89 ± 0.10 events d^{-1} of βn -decays are removed from the data sample. The residual cosmogenic isotope background rate has been determined to 1.25 ± 0.54 events/day.

Finally, the correlation of parent muons and βn -emitters has been used to extract the prompt β spectrum from the data. Figure 10 shows a sample spectrum obtained for $E_\mu > 620$ MeV, a distance cut of 0.7 m and a $\Delta t_{\mu\nu}$ cut of 600 ms. The contamination of the sample by random coincidences has been statistically subtracted. Good agreement is found for the MC spectrum used in the final fit analysis.

D. Fast Neutrons and Stopping Muon Background

Most correlated backgrounds are rejected by the 1 ms veto time after each tagged muon. The remaining events arise from cosmogenic events whose parent muon either misses the detector or deposits an energy low enough to escape the muon tagging. Two contributions have been found: fast neutrons (FN) and stopping muons (SM).

FN are created by muons in the inactive regions surrounding the detector. Their large interaction length allows them to cross the detector and capture in the ID, causing both a prompt trigger by recoil protons and a delayed trigger by capture on Gd. An approximately flat prompt energy spectrum is expected; a slope could be introduced by acceptance and scintillator quenching effects. The time and spatial correlation distribution of FN are indistinguishable from those of $\bar{\nu}_e$ events.

The selected SM arise from muons entering through the chimney, stopping in the top of the ID, and eventually decaying. The short muon track mimics the prompt event, and the decay Michel electron mimics the delayed event. SM candidates are localized in space in the top of the ID under the chimney, and have a prompt-delayed time distribution following the $2.2 \mu\text{s}$ muon lifetime.

The correlated background has been studied by extending the selection on E_{prompt} up to 30 MeV. No IBD events are expected in the interval $12 \text{ MeV} \leq E_{\text{prompt}} \leq 30 \text{ MeV}$. FN and SM candidates were separated via their different correlation time distributions. A $97^{+3}_{-8}\%$ pure sample of FN is obtained for $\Delta T > 10 \mu\text{s}$, and a $(88 \pm 7)\%$ pure sample of SM is obtained for $\Delta T < 10 \mu\text{s}$. These samples of FN and SM can be used to estimate their rate. The observed prompt energy spectrum is consistent with a flat continuum between 12 and 30 MeV, which extrapolated to the IBD selection window provides a first estimation of the correlated background rate of ≈ 0.75 events/day. The accuracy of this estimate depends on the validity of the extrapolation of the spectral shape. Next we describe a measurement of the FN and SM spectral shapes including the IBD region, obtained by using the IV and OV to tag samples of FN and SM.

The DAQ reads out the IV upon any ID trigger, lowering the IV detection threshold to ~ 1 MeV, and making the IV sensitive to FN via the detection of proton recoils and captures on H. The IV-tagging is implemented by demanding at least 2 IV PMT hits leading to $(33 \pm 5)\%$ tagging efficiency with no contribution by single PMT energy depositions. There is a very low probability of accidental IV tagging due to any IV energy deposition in the 256 ns coincident readout window.

The OV-tagging, when available, is especially sensitive to SMs since the muon is often detected. $(41 \pm 23)\%$ of the FN and SM candidates in the 12-to-30-MeV window are tagged by the OV, of which $(74 \pm 12)\%$ are SM. OV-tagging has an accidental rate = 0.06% of the neutrino sample and can be used to veto events caused by muons.

Several FN and SM analyses were performed using different combinations of IV and OV tagging. The main analysis for the FN estimation relies on IV-tagging of the prompt triggers with OV veto applied for the IBD selection. Two sources of backgrounds on the tagged FN sample were identified and rejected. The first source is the combination of natural radioactivity in the IV in an accidental coincidence with a genuine IBD, and was reduced to 12% by imposing a time coincidence between the ID and IV energy depositions. The second source, a Comp-

FIG. 11. FN and SM combined spectral model best fit (solid red) with $\pm 1\sigma$ (dashed red), energy distribution of tagged FN and SM population (gray histogram) and IBD spectrum.

ton scattering in both the IV and ID in an accidental coincidence with a Gd-capture, was reduced to 2% by imposing a cut on the spatial distance between the prompt and delayed candidate in the ID. The purity of the IV-tagged FN sample was 86%. The remaining background was measured in an off-time window and subtracted, thus minimizing distortions to the energy spectrum. The FN spectral shape was found to be in agreement with a linear model with a small positive slope. The measured total FN rate was (0.30 ± 0.14) events/day, including systematic uncertainties from the ΔT -based FN-SM separation, the IV-tagging efficiency, and background subtractions.

Since there is no correlation between the SM prompt energy and the delayed energy deposit of the Michel electron, a pure sample of SM was obtained by selecting $20 \text{ MeV} \leq E_{\text{delayed}} \leq 60 \text{ MeV}$. The spectral shape of SM prompt energy was found to be in agreement with a linear model with a small negative slope. The total SM rate was measured to be (0.34 ± 0.18) events/day, including systematic uncertainties.

Since the spectral shapes for both FN and SM are linear, a combined analysis was performed to obtain the total spectrum shown in Fig. 11 and the total rate estimation (0.67 ± 0.20) events/day summarized in Table V. Consistent results were obtained from different analysis techniques, which included IV- and OV-tagging without OV-vetoing. The OV veto reduces the rate of correlated backgrounds by about 30%.

E. Background Measurements

There are four ways that can be utilized to estimate backgrounds. Each independent background component can be measured by isolating samples and subtracting possible correlations. This is described for each component in Sections IV D, V C and V D. Second, we can measure each independent background component including spectral information when fitting for θ_{13} oscillations as is done in Section VI. Third, the total background rate is

measured by comparing the observed and expected rates as a function of reactor power. Fourth, we can use the both-reactor-off data to measure both the rate and spectrum.

The latter two methods are used currently as cross-checks for the background measurements due to low statistics and are described here. The measured daily rate of IBD candidates as a function of the no-oscillation expected rate for different reactor power conditions is shown in Figure 12. The extrapolation to zero reactor power of the fit to the data yields 2.9 ± 1.1 events per day, in excellent agreement with our background estimate. The overall rate of correlated background events that pass the IBD cuts is independently verified by analyzing 22.5 hours of both-reactors-off data. The expected neutrino signal is < 0.3 residual $\bar{\nu}_e$ events. Three events passed the first 4 cuts in Section V A. Two events with prompt energies of 4.8 MeV and 9.4 MeV were associated within 30 cm and 240 ms with the closest energetic muon, and are thus likely to be associated with ^9Li . Indeed, the second candidate is rejected by the showering muon veto. The third candidate at a prompt energy of 0.8 MeV features 3.5 m distance between prompt and delayed events and is therefore most likely a random coincidence. Immediately following the data set used in this paper, we obtained a larger data set with both-reactors-off. That will be the subject of a separate paper [59].

FIG. 12. Daily number of $\bar{\nu}_e$ candidates as a function of the expected number of $\bar{\nu}_e$. The dashed line shows the fit to the data, along with the 90% C.L. band. The dotted line shows the expectation in the no-oscillation scenario.

F. Neutron Detection Efficiency

Calibration data taken with the ^{252}Cf source were used to check the Monte Carlo prediction for any biases in the neutron selection criteria and estimate their contributions to the systematic uncertainty.

The fraction of neutron captures on gadolinium is evaluated to be 86.5% near the center of the target, 1.5% lower than the fraction predicted by simulation. Therefore the Monte Carlo simulation for the prediction of the number of $\bar{\nu}_e$ events is reduced by factor of 0.985. After the prediction of the fraction of neutron captures on gadolinium is scaled to the data, the prediction reproduces the data to within 0.3% under variation of selection criteria.

The ^{252}Cf is also used to check the neutron capture time, ΔT . The time difference between the prompt event and neutron capture signal for the californium calibration data is shown in Figure 13. The simulation reproduces the efficiency (96.2%) of the Δt_{e+n} cut with an uncertainty of 0.5% augmented with sources deployed through the NT and GC.

The efficiency for Gd capture events with visible energy greater than 4 MeV to pass the 6 MeV cut is estimated to be 94.1%. Averaged over the NT, the fraction of neutron captures on Gd accepted by the 6.0 MeV cut is in agreement with calibration data to within 0.7%.

The Monte Carlo simulation indicates that the number of IBD events occurring in the GC with the neutron captured in the NT (spill-in) slightly exceeds the number of events occurring in the target with the neutron escaping to the gamma catcher (spill-out), by $1.35\% \pm 0.04\%$ (stat) $\pm 0.30\%$ (sys). The spill-in/out effect is already included in the simulation and therefore no correction for this is needed. The uncertainty of 0.3% assigned to the net spill-in/out current was quantified by varying the parameters affecting the process, such as gadolinium concentration in the target scintillator and hydrogen fraction in the gamma-catcher fluid within its tolerances. Moreover the parameter variation was performed with multiple Monte Carlo models at low neutron energies.

VI. OSCILLATION ANALYSIS

The oscillation analysis is based on a combined fit to antineutrino rate and spectral shape. IBD candidates are selected as described in Section V A. The data are compared to the Monte Carlo signal and background events from high-statistics samples. The same selections are applied to both signal and background, with corrections made to Monte Carlo only when necessary to match detector performance metrics.

The oscillation analysis begins by separating the data into 18 variably-sized bins between 0.7 and 12.2 MeV. Two integration periods are used in the fit to help separate background and signal flux. One set contains data periods where one reactor is operating at less than 20% of

FIG. 13. Time difference between prompt and delayed events with ^{252}Cf at the detector center. The prompt time is determined by 7-30 MeV gamma ray.

its nominal thermal power, according to power data provided by EDF, while the other set contains data from all other times, typically when both reactors are running. All data end up in one of the two integration periods. Here, we denote the number of observed IBD candidates in each of the bins as N_i , where i runs over the combined 36 bins of both integration periods. The use of multiple periods of data integration takes advantage of the different signal/background ratios in each period, as the signal rate varies with reactor power while the backgrounds remain constant in time. This technique adds information about background behavior to the fit. The distribution of IBD candidates between the two integration periods is given in Table V.

A prediction of the observed number of signal and background events is constructed for each energy bin, following the same integration period division as the data:

$$N_i^{\text{pred}} = \sum_{R=1,2}^{\text{Reactors}} N_i^{\nu,R} + \sum_b^{\text{Bkgnds.}} N_i^b \quad (13)$$

where $N_i^{\nu,R} = P(\bar{\nu}_e \rightarrow \bar{\nu}_e) N_i^{\text{exp},R}$; $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ is the neutrino survival probability from the well-known oscillation formula and $N_i^{\text{exp},R}$ is given by Equation 4. The index b runs over the three backgrounds: cosmogenic isotope; correlated; and accidental. The index R runs over the two reactors, Chooz B1 and B2.

Background populations were calculated based on the measured rates and the livetime of the detector during each integration period. Details on the signal prediction normalization can be found in Sec. III D. Predicted populations for both null-oscillation signal and backgrounds may be found in Table V.

Systematic and statistical uncertainties are propagated to the fit by the use of a covariance matrix M_{ij} in order to properly account for correlations between energy bins.

	Reactors Both On	One Reactor $P_{th} < 20\%$	Total
Livetime [days]	139.27	88.66	227.93
IBD Candidates	6088	2161	8249
ν Reactor B1	2910.9	774.6	3685.5
ν Reactor B2	3422.4	1331.7	4754.1
Cosmogenic Isotope	174.1	110.8	284.9
Correlated FN & SM	93.3	59.4	152.7
Accidentals	36.4	23.1	59.5
Total Prediction	6637.1	2299.7	8936.8

TABLE V. Summary of observed IBD candidates, with corresponding signal and background predictions for each integration period, before any oscillation fit results have been applied.

The sources of uncertainty A are listed in Table VI.

$$M_{ij} = M_{ij}^{\text{sig.}} + M_{ij}^{\text{det.}} + M_{ij}^{\text{stat.}} + M_{ij}^{\text{eff.}} + \sum_b^{\text{Bkgnds.}} M_{ij}^b \quad (14)$$

Each term $M_{ij}^A = \text{cov}(N_i^{\text{pred}}, N_j^{\text{pred}})_A$ on the right-hand side of Equation 14 represents the covariance of N_i^{pred} and N_j^{pred} due to uncertainty A . The normalization uncertainty associated with each of the matrix contributions may be found from the sum of each matrix: these are summarized in Table VI. Many sources of uncertainty contain spectral shape components which do not directly contribute to the normalization error, but do provide for correlated uncertainties between the energy bins. The signal covariance matrix $M_{ij}^{\text{sig.}}$ is calculated taking into account knowledge about the predicted neutrino spectra. The ^9Li matrix contribution contains spectral shape uncertainties estimated using different Monte Carlo event generation parameters, as described in Sec. III E. The slope of the FN/SM spectrum is allowed to vary from a nearly-flat spectrum following the measurements described in Section V D. Since accidental background uncertainties are measured to a high precision from many off-time windows, they are included as a diagonal covariance matrix.

The elements of the covariance matrix contributions are recalculated as a function of the oscillation and other parameters (see below) at each step of the minimization. This maintains the fractional systematic uncertainties as the bin populations vary from the changes in the oscillation and fit parameters.

A fit of the binned signal and background data to a two-neutrino oscillation hypothesis was performed by

Source	Uncertainty [%]
Reactor Flux	1.67%
Detector Response	0.32%
Statistics	1.06%
Efficiency	0.95%
Cosmogenic Isotope Background	1.38%
FN/SM	0.51%
Accidental Background	0.01%
Total	2.66%

TABLE VI. Summary of signal and background normalization uncertainties in this analysis relative to the total prediction.

minimizing a standard χ^2 function:

$$\begin{aligned}
\chi^2 = & \sum_{i,j}^{36} \left(N_i - N_i^{\text{pred}} \right) \\
& \times \left(M_{ij} \right)^{-1} \left(N_j - N_j^{\text{pred}} \right)^T \\
& + \frac{(\epsilon_{FN/SM} - 1)^2}{\sigma_{FN/SM}^2} + \frac{(\epsilon_{9\text{Li}} - 1)^2}{\sigma_{9\text{Li}}^2} \\
& + \frac{(\alpha_E - 1)^2}{\sigma_{\alpha_E}^2} + \frac{(\Delta m_{31}^2 - (\Delta m_{31}^2)_{\text{MINOS}})^2}{\sigma_{\text{MINOS}}^2} \quad (15)
\end{aligned}$$

The use of energy spectrum information in this analysis allows additional information on background rates to be gained from the fit, in particular because of the small number of IBD events between 8 and 12 MeV. The two fit parameters $\epsilon_{FN/SM}$ and $\epsilon_{9\text{Li}}$ are allowed to vary as part of the fit, and they scale the rates of the two backgrounds (correlated and cosmogenic isotope). The rate of accidentals is not allowed to vary since its initial uncertainty is precisely determined by the measurement method described in Sec. V B. The energy scale for predicted signal and ^9Li events is allowed to vary linearly according to the α_E parameter with an uncertainty $\sigma_{\alpha_E} = 1.13\%$. A final parameter constrains the mass splitting Δm_{31}^2 using the MINOS measurement [60] of $\Delta m_{31}^2 = (2.32 \pm 0.12) \times 10^{-3} \text{ eV}^2$, where we have symmetrized the error. This error includes the uncertainty introduced by relating the effective mass-squared difference observed in a ν_μ disappearance experiment to the one relevant for reactor experiments, and the ambiguity due to the type of the neutrino mass hierarchy, see e.g. [61]. Uncertainties for these parameters, $\sigma_{FN/SM}$, $\sigma_{9\text{Li}}$, and σ_{MINOS} , are listed as the initial values in Table VII.

The best-fit gives $\sin^2 2\theta_{13} = 0.109 \pm 0.030 \text{ (stat.)} \pm 0.025 \text{ (syst)}$ at $\Delta m_{31}^2 = 2.32 \times 10^{-3} \text{ eV}^2$, with a $\chi^2/\text{NDF} = 42.1/35$. We used the MINOS measured Δm_{31}^2 value as a constraint for our θ_{13} measurement, but a two parameter fit without the MINOS Δm_{31}^2 in the region $\Delta m_{31}^2 < 0.01 \text{ eV}^2$ gives a Δm_{31}^2 value of $2.7 \pm 1.9 \times 10^{-3} \text{ eV}^2$, which is fully consistent with MINOS. The fit gives $\sin^2 2\theta_{13} = 0.093 \pm 0.078$ which is consistent with our fit for θ_{13} using MINOS.

Table VII gives the resulting values of the fit parameters and their uncertainties. Comparing the values with the ones used as input to the fit in Table V we conclude that the background rate and uncertainties are further constrained in the fit, as well as the energy scale.

The final measured spectrum and the best-fit spectrum are shown in Figure 14 for the new and old data sets, and for both together in Figure 15.

Fit Parameter	Initial Value	Best-Fit Value
^9Li Bkg. $\epsilon_{9\text{Li}}$	$(1.25 \pm 0.54) \text{ d}^{-1}$	$(1.00 \pm 0.29) \text{ d}^{-1}$
FN/SM Bkg. $\epsilon_{FN/SM}$	$(0.67 \pm 0.20) \text{ d}^{-1}$	$(0.64 \pm 0.13) \text{ d}^{-1}$
Energy Scale α_E	1.000 ± 0.011	0.986 ± 0.007
$\Delta m_{31}^2 (10^{-3} \text{ eV}^2)$	2.32 ± 0.12	2.32 ± 0.12

TABLE VII. Parameters in the oscillation fit. Initial values are determined by measurements of background rates or detector calibration data. Best-fit values are outputs of the minimization procedure.

An analysis comparing only the total observed number of IBD candidates in each integration period to the expectations produces a best-fit of $\sin^2 2\theta_{13} = 0.170 \pm 0.052$ at $\chi^2/\text{NDF} = 0.50/1$. The compatibility probability for the rate-only and rate+shape measurements is about 30% depending on how the correlated errors are handled between the two measurements.

A re-processing of the data set used for the first Double Chooz publication [7] was performed using the current analysis techniques. A fit using only a single integration period yielded a best-fit value of $\sin^2 2\theta_{13} = 0.0744 \pm 0.046$ with $\chi^2/\text{NDF} = 18.3/17$. An analysis of only the data taken since the first publication yielded a best-fit of $\sin^2 2\theta_{13} = 0.143 \pm 0.043$ with $\chi^2/\text{NDF} = 9.54/17$. The data and best-fit spectra for each of these cases is shown in Figure 16.

Our predicted fission cross section is $5.723 \pm 0.096 \times 10^{-43} \text{ cm}^2/\text{fission}$ using the Bugey4 anchoring measurement and corresponding to the values of α_k in Table I. The background subtracted reactor antineutrino event rate is 7751.9 events, corresponding to 91.85% of the rate expected in the absence of oscillations. Our measured fission cross section is $5.257 \pm 0.056 \text{ (stat.)} \pm 0.105 \text{ (syst)} \times 10^{-43} \text{ cm}^2/\text{fission}$.

A further cross-check of the analysis was carried out by imposing cuts to eliminate the vast majority of the cosmogenic isotope background at the cost of reduced livetime. The best-fit case of this analysis was found at $\sin^2 2\theta_{13} = 0.109 \pm 0.044$ and $\Delta m_{31}^2 = 2.32 \times 10^{-3} \text{ eV}^2$, in good agreement with the standard analysis.

Confidence intervals for the standard analysis were determined using a frequentist technique [62]. This approach accommodates the fact that the true χ^2 distributions may not be Gaussian and is useful for calculating the probability of excluding the no-oscillation hypothesis. This study compared the data to 10,000 simulations generated at each of 21 test points in the range $0 \leq \sin^2 2\theta_{13} \leq 0.25$. A $\Delta\chi^2$ statistic, equal to the difference between the χ^2 at the test point and the χ^2 at

FIG. 14. Measured prompt energy spectrum for each integration period (data points) superimposed on the expected prompt energy spectrum, including backgrounds (green region), for the no-oscillation (blue dotted curve) and best-fit (red solid curve) at $\sin^2 2\theta_{13} = 0.109$ and $\Delta m_{31}^2 = 2.32 \times 10^{-3} \text{ eV}^2$. Inset: stacked spectra of backgrounds. Bottom: differences between data and no-oscillation prediction (data points), and differences between best fit prediction and no-oscillation prediction (red curve). The orange band represents the systematic uncertainties on the best-fit prediction.

FIG. 15. Sum of both integration periods plotted in the same manner as Figure 14.

the best fit, was used to determine the region in $\sin^2 2\theta_{13}$

where the $\Delta\chi^2$ of the data was within the given confidence probability. The allowed region at 68% (90%) CL is $0.067 \text{ (0.043)} < \sin^2 2\theta_{13} < 0.15 \text{ (0.18)}$. An analogous technique shows that the data excludes the no-oscillation hypothesis at 99.8% (2.9σ).

VII. CONCLUSION

A comparison of this analysis result to other recent $\sin^2 2\theta_{13}$ measurements by other experiments is shown in Figure 17. The figure shows published results, though we note that new results from Daya Bay, MINOS and T2K have been shown at conferences but are not yet published [63]. The values for $\sin^2 2\theta_{13}$ from the various experiments are in excellent agreement with the results reported here. However this result is unique in its incorporation of energy dependence in the analysis.

Double Chooz has found evidence for a non-zero value of θ_{13} from the rate and energy spectrum of reactor neutrino candidates at a distance of 1050 m from two reactors. It is the first evidence for this parameter using the energy spectrum from reactor neutrinos, rather than simply their rate. We find a best fit value and 1σ error to be $\sin^2 2\theta_{13} = 0.109 \pm 0.030 \text{ (stat)} \pm 0.025 \text{ (syst)}$. The data is inconsistent with the assumption that oscillations

(a) First Publication Data Set

(b) Data Since First Publication

FIG. 16. Data and best-fit spectrum from applying current analysis techniques to the data set used to produce the first Double Chooz publication (a), and data taken since that publication (b), plotted in the same manner as Figure 14.

are absent with a CL of 99.8% CL (2.9σ).

We thank the French electricity company EDF, the European fund FEDER, the Région de Champagne Ardenne, the Département des Ardennes and the Communauté des Communes Rives de Meuse. We acknowledge the support of CEA and CNRS/IN2P3 in France,

FIG. 17. Comparison of recent reactor- and accelerator-based measurements of $\sin^2 2\theta_{13}$ from this analysis, the first Double Chooz publication [7], Daya Bay [8], RENO [9], T2K [6], and MINOS [5]. Error bars correspond to 1σ . For T2K and MINOS the CP phase δ has been fixed (arbitrarily) to $\delta = 0$.

French LabEx UnivEarthS, Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) and Japan Society for the Promotion of Science (JSPS), the Department of Energy and the National Science Foundation of the United States, the Ministerio de Ciencia e Innovación (MICINN) of Spain, the Max Planck Gesellschaft and the Deutsche Forschungsgemeinschaft DFG (SBH WI 2152), the Transregional Collaborative Research Center TR27, the Excellence Cluster "Origin and Structure of the Universe" and the Maier-Leibnitz-Laboratorium Garching, the Russian Academy of Science, the Kurchatov Institute and RFBR (the Russian Foundation for Basic Research), the Brazilian Ministry of Science, Technology and Innovation (MCTI), the Financiadora de Estudos e Projetos (FINEP), the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), the São Paulo Research Foundation (FAPESP), the Brazilian Network for High Energy Physics (RENAFAE) in Brazil and the computer center CCIN2P3.

-
- [1] M. Appolonio et al., Phys. Lett., B466, 415 (1999).
 - [2] G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A. M. Rotunno, Phys. Rev. D84, 053007 (2011).
 - [3] The KamLAND Collaboration, Phys. Rev. D83, 052002 (2011).
 - [4] T. Schwetz et al., New J. Phys. 13, 109401 (2011).
 - [5] P. Adamson et al., Phys. Rev. Lett. 107, 181802 (2011).
 - [6] K. Abe et al., Phys. Rev. Lett. 107, 041801 (2011).
 - [7] Y. Abe et al., Phys. Rev. Lett. 108, 131801 (2012).
 - [8] F. P. An et al., Phys. Rev. Lett. 108, 171803 (2012).
 - [9] J. K. Ahn et al., Phys. Rev. Lett. 108, 191802 (2012).
 - [10] F. Ardellier et al., (Double Chooz Collaboration) (2006) hep-ex/0606025.
 - [11] T. Matsubara et al., Nucl. Instrum. Meth., A661, 16, 2011.
 - [12] C. Bauer et al., JINST, 6, P06008 (2011).
 - [13] E. Calvo et al., Nucl. Instrum. Meth., A621, 222 (2010).
 - [14] M. Fechner et al., Applied Radiation and Isotopes, 69(7), 1033 (2011).
 - [15] G. Heusser, M. Laubenstein, H. Neder, Radionuclides in the environment, Int. Conf. on Isotopes in Environmental Studies, edited by P. P. Povinec and J. A. Sanchez-Cabeza, Elsevier, Amsterdam 495 (2006).
 - [16] C. Aberle et al., JINST, 7, P06008 (2012).
 - [17] M. Hofmann, Ph.D. thesis, Technische Universität München (2012).
 - [18] Measured by A. Smith at the LBNL Low Background Facility with the MERLIN n-type HPGe detector.
 - [19] S. Abe et al., Phys. Rev. C81, 025807 (2010).
 - [20] M. Apollonio et al., Eur. Phys. J, C27, 331 (2003).
 - [21] C. Aberle, C. Buck, F.X. Hartmann and S. Schönert, Chem. Phys. Lett., 516, 257 (2011).
 - [22] http://jp.hamamatsu.com/resources/products/etd/pdf/LARGE_AREA_PMT_TPMH1286E05.pdf.
 - [23] F. Kaether and C. Langbrandtner, arXiv:1207.0378 (submitted to JINST).
 - [24] D. Dietrich et al. "Monte Carlo aided design of the Inner Muon Veto detectors for the Double Chooz experiment" (2012), accepted for publication in JINST.
 - [25] K. Zbiri, arXiv:1104.4045 (2011).
 - [26] Max Perles et al., http://www.maxperles.com/pdf/ftch_fr/ft_ar100clx_nov10.pdf (2012).
 - [27] F. Beissel et al., "The Trigger and Timing System of the Double Chooz Experiment" (submitted to JINST).
 - [28] A. Cabrera, Nucl. Instrum. Meth. Phys. Res., Sect. A 617, 473 (2010).
 - [29] T. Akiri, Ph.D. thesis, Universite Paris-Diderot, (2010).
 - [30] CAEN Corporation, <http://www.caen.it/>. The device was co-developed with APC.
 - [31] P. Barrillon et al., MAROC: Multi-Anode ReadOut Chip for MAPMTs, proceedings of 2007 IEEE conference (2007), P. Barrillon et al., 64-channel Front-End read-out chip, MAROC2 datasheet, <http://omega.in2p3.fr/>.
 - [32] E. Tournu et al., EDF TechnicalNote (2001).
 - [33] Standard AFNOR XP X 07-020 (1996).
 - [34] Y. Caffari, J.M. Favenne, EDF tech-note H-P1C-2011-02007-FR.
 - [35] Z. Djuric et al., J. Phys. G36, 045002 (2009).
 - [36] K. Schreckenbach, G. Colvin, and F. von Feilitzsch, Phys. Lett. 160B, 325 (1985).
 - [37] F. von Feilitzsch and K. Schreckenbach, Phys. Lett. 118B, 162 (1982).
 - [38] A. Hahn et al., Phys. Lett. B 218, 365 (1989).
 - [39] T. Mueller et al., Phys. Rev. C83, 054615 (2011).
 - [40] P. Huber, Phys. Rev. C84, 024617 (2011).
 - [41] G. Mention et al., Phys. Rev. D83, 073006 (2011).
 - [42] O. Meplan et al., in ENC 2005: European Nuclear Conference; Nuclear power for the XXIst century: from basic research to high-tech industry (2005).
 - [43] NEA-1845/01, documentation for MURE (2009).
 - [44] G. Marleau et al., Report IGE-157 (1994).
 - [45] C. Jones, "Prediction of the Reactor Antineutrino Flux for the Double Chooz Experiment", Ph.D. thesis, MIT (2012).
 - [46] C. Jones et al., arXiv:1109.5379v1 (2011).
 - [47] V. Kopeikin, L. Mikaelyan, and V. Sinev, Phys. At. Nucl. 67, 1892 (2004).
 - [48] Y. Declais et al., Phys. Lett. B338, 383 (1994).
 - [49] P. Vogel and J. F. Beacom, Phys. Rev. D60, 053003 (1999).
 - [50] A. Pichlmaier et al., Phys. Lett. B693, 221 (2010).
 - [51] J. Allison et al., IEEE Trans. Nucl. Sci. 53 No. 1, 270 (2006), S. Agostinelli et al., Nucl. Instrum. Meth. A506, 250 (2003).
 - [52] J. Apostolakis et al., "Geant4 Physics Lists for HEP," Nuclear Science Symposium Conference Record, IEEE, 833 (2008).
 - [53] J.B. Birks, Proc. Phys. Soc. A64, 874 (1951); 64, 511 (1951).
 - [54] D. Motta and S. Schönert, Nucl. Instrum. Meth. A539, (2005) 217.
 - [55] D. R. Tilley et al., Nucl. Phys. A745, 155 (2004), Y. Prezado, et al., Physics Letters B618, 43.50 (2005), P. Papka, et al., Phys. Rev. C 75, 045803 (2007).
 - [56] <http://www.chem.agilent.com/en-US/Products/instruments/molecularspectroscopy/fluorescence/systems/caryclipse/pages/default.aspx>.
 - [57] C. Aberle, C. Buck, F.X. Hartmann, S. Schönert and S. Wagner, JINST 6, P11006 (2011).
 - [58] C. Aberle, Ph.D. thesis, Universität Heidelberg (2011).
 - [59] Y. Abe et al., in preparation.
 - [60] P. Adamson et al., Phys. Rev. Lett. 106, 181801 (2011).
 - [61] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D72, 013009 (2005).
 - [62] G.J. Feldman and R.D. Cousins, Phys. Rev. D57, 3873 (1998).
 - [63] Proceedings of the XXXV International Conference on Neutrino Physics and Astrophysics, June 3-9, 2012, Kyoto, Japan, to be published.

First result from the Double Chooz reactor-neutrino experiment

T. Matsubara on behalf of the Double Chooz collaboration
Department of Physics, Tokyo Metropolitan University, Japan

We report first results of a search for the non-zero neutrino mixing angle θ_{13} from the Double Chooz experiment. Double Chooz aims to measure the mixing angle based on $\bar{\nu}_e$ disappearance as a consequence of neutrino oscillation. A new generation of $\bar{\nu}_e$ detector having 10 m^3 fiducial volume is located 1 km from the two 4.25 GW_{th} reactors at the Chooz Power Plant in France. Physics data taking has been continuing since April 2011. A ratio of observed-to-predicted event rate of $0.944 \pm 0.016\text{ (stat)} \pm 0.040\text{ (syst)}$ was obtained in 101 days of detector running. Analyzing both the rate and their energy spectral shape, we found $\sin^2 2\theta_{13} = 0.086 \pm 0.041\text{ (stat)} \pm 0.030\text{ (syst)}$ at $\Delta m_{atm}^2 = 2.4 \times 10^{-3}\text{ eV}^2$.

1 Introduction

Prior to one year ago, the neutrino mixing angle θ_{13} had been an unknown parameter in the neutrino oscillation framework. The best constraint on θ_{13} was come from the CHOOZ reactor-neutrino experiment¹, $\sin^2 2\theta_{13} < 0.15$ (90% C.L. at $\Delta m_{atm}^2 = 2.5 \times 10^{-3}\text{ eV}^2$). The T2K and MINOS accelerator experiments recently reported a sign of non-zero θ_{13} with ν_e appearance^{2,3}. First reactor experiment to present a result was Double Chooz, which reported an indication for a disappearance of reactor $\bar{\nu}_e$ in November 2011⁴. Other two reactor-neutrino experiments, Daya Bay and RENO, gave consistent results with higher sensitivity in early 2012^{5,6}. These results supporting relatively large θ_{13} value, $\sin^2 2\theta_{13} \sim 0.1$, potentially encourage us to measure a leptonic CP violation in near future experiments. This paper describes the first results of a search for the non-zero neutrino mixing angle θ_{13} from the Double Chooz experiment.

Neutrino oscillation occurs as a consequence of non-zero mass and a mixing of mass eigenstates and flavor eigenstates. In the reactor-neutrino experiments, survival probability of $\bar{\nu}_e$ is given by:

$$P_{surv} \simeq 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{atm}^2 L/E), \quad (1)$$

where $\Delta m_{atm}^2\text{ (eV}^2\text{)}$ is the atmospheric squared mass difference, which is precisely measured by the MINOS experiment⁷. L is the reactor-to-detector distance in meters and E the $\bar{\nu}_e$ energy in MeV. This formula indicates the $\sin^2 2\theta_{13}$ measurability by observing $\bar{\nu}_e$ disappearance at appropriate baseline. We therefore placed a $\bar{\nu}_e$ detector located at $\sim 1050\text{ m}$ under a $\sim 300\text{ m.w.e.}$ rock overburden from the two 4.25 GW_{th} reactors at the Chooz Power Plant in France. In order to reduce systematic uncertainties such as neutrino flux, we will operate an identical detector located at $\sim 400\text{ m}$ baseline under a $\sim 120\text{ m.w.e.}$ rock overburden by 2013. The $\bar{\nu}_e$'s are detected through the inverse beta decay (IBD) reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$. Detector based on hydrocarbon liquid scintillator provides free proton target and reacts with $\bar{\nu}_e$. Positron ionization and annihilation ($1\sim 8\text{ MeV}$) then creates a prompt signal. Neutron capture on Gadolinium

(~ 8 MeV) creates a delayed signal. The signature of IBD reaction is identified by a time coincidence of $\tau \sim 30 \mu\text{s}$ between those signals. In this reaction, the $\bar{\nu}_e$ energy can be reconstructed with prompt energy as: $E_{\text{prompt}} = E(\text{kin.})_{e^+} + 2m_e \simeq E_{\bar{\nu}_e} - (M_n - M_p) + m_e \simeq E_{\bar{\nu}_e} - 0.782 \text{ MeV}$.

A new generation of $\bar{\nu}_e$ detector for the Double Chooz experiment (Figure 1) consists of a main detector, an outer veto and calibration devices. The main detector is separated into four concentric cylindrical tanks. Innermost 8 mm thick transparent acrylic vessel is called neutrino-target region. The region is filled with a liquid scintillator with a mixture of n-dodecane, PXE, PPO, bis-MSB and 1 g/l Gadolinium as a beta-diketonate complex. This structure contains a fiducial volume for the neutrino events within 10 m^3 of the target vessel. The composition is chosen for radiopurity and long-term stability. Gamma-catcher region surrounds the target vessel to detect γ -rays escaped from neutrino-target region. It consists of 12 mm thick transparent acrylic vessel containing 22.3 m^3 of liquid scintillator. Buffer region is located outside of the gamma-catcher region. The region is filled with 110 m^3 of mineral oil to shield γ -rays from the Photo Multiplier Tubes (PMT) and rocks. Total 390 10-inch low-radioactive PMTs are equipped at the inner wall of stainless steel buffer tank to observe light from the inner volumes. These three layers constitute the inner detector (ID). The ID is surrounded by the optically separated region of the inner veto (IV) equipped with 78 8-inch PMTs. 90 m^3 liquid scintillator is filled in a steel tank for muon veto and shielding of spallation neutrons produced outside of the detector. The detector is surrounded by 150 mm of demagnetized steel to reduce a contamination due to external γ -rays. Outer veto system lies on main detector, which is not used for this analysis. The main detector is read out with 500 MHz flash-ADC electronics with customized firmware and a deadtime-free acquisition system.

Figure 1: A schematic view of the Double Chooz detector.

2 Neutrino prediction and data analysis

The analysis is based on 101.5 days of data including 16 days with one reactor off and one day with both reactors off. The expected number of $\bar{\nu}_e$'s are predicted as:

$$N_{\nu}^{exp}(E, t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle, \quad (2)$$

where N_p is the number of protons in the detector, ϵ the detection efficiency, $P_{th}(t)$ the thermal power of reactor, $\langle E_f \rangle$ the mean energy per fission and $\langle \sigma_f \rangle$ the mean cross-section per fission. Mean energy per fission and associated errors are evaluated with two reactor simulation codes, MURE⁸ and DRAGON⁹. Mean cross-section per fission and associated errors are estimated with updated reference spectra¹⁰. Neutrino prediction is based on Bugey4 measurement¹¹ as an anchor point of the mean cross-section with correction to Chooz reactor. Total systematic uncertainty on reactor is estimated to be 1.8%.

Energy measurements for data analysis are based on the total charge collected by the PMTs. The energy is reconstructed scaling the total charge by a constant corresponding to ~ 200 p.e./MeV, which is adjusted with the 2.2 MeV energy peak of neutron capture on H at the target center. Our Monte Carlo simulation based on GEANT4 is used to calculate the detector response. Comparison between actual and simulated calibration data has been done to correct the simulation and estimate an associated uncertainty to be 1.7%, using two parametric functions with respect to energy and position.

We applied the following criteria to select $\bar{\nu}_e$ candidates. Triggers within a 1000 μ s after a cosmic muon crossing the ID or IV are vetoed to suppress spallation neutrons and cosmogenic backgrounds. This requirement is followed by five selections: (1) a cut rejecting events caused by sporadically glowing PMT bases, resulting in light localized to a few PMTs and spread out in time: $Q_{max}/Q_{tot} < 0.09$ (0.06) for the prompt (delayed) energy and $rms(t_{start}) < 40$ ns, where Q_{max} is the maximum charge recorded by a single PMT and $rms(t_{start})$ is the standard deviation of the times of the first pulse on each PMT; (2) $0.7 \text{ MeV} < E_{prompt} < 12.2 \text{ MeV}$; (3) $6.0 \text{ MeV} < E_{delayed} < 12.0 \text{ MeV}$; (4) $2 \mu\text{s} < \Delta t_{e+n} < 100 \mu\text{s}$; (5) a multiplicity cut to reject correlated backgrounds defined as no additional valid trigger from 100 μ s preceding the prompt candidate to 400 μ s after it. In total, 4121 neutrino candidates were observed, which is equal to 42.6 ± 0.7 events/day on average (Figure 2).

Backgrounds mimicking the time coincidence have been estimated as follows. Accidental background caused by uncorrelated coincidence, for example, prompt event from radioactivity and delayed event from cosmogenic neutron capture. This background rate is estimated by sequentially shifted off-time window, leading 0.33 ± 0.03 events/day. Fast neutron induced by muon traveling the rock can interact in the detector producing recoil proton. Thermalized and captured neutron accompanying the recoil proton then mimics the IBD events. We estimated the rate to be 0.83 ± 0.38 event/day by modifying the E_{prompt} selection criteria to be $12.2 \text{ MeV} < E_{prompt} < 30 \text{ MeV}$ and extrapolating to the signal region assuming flat energy spectrum. Spallation product of ^9Li induced by energetic muons emits n and β , simulating IBD event. This background is studied by time distribution between a muon energy deposition $> 600 \text{ MeV}$ and neutrino candidates. Fitting the time distribution by a flat component and an exponential with the ^9Li lifetime results in 2.3 ± 1.2 events/day. We account for a shape uncertainty between some decay branches.

We had a chance to take data with both reactors off for ~ 24 hours. It was an unique opportunity to validate our background estimation. Two candidates in neutrino energy window following high energy muon were observed, which are compatible with candidates of ^9Li background. This result is consistent with the estimated number of BG events (Total 3.46 ± 1.26 events/day).

Neutrino candidates rate (background not subtracted)

Figure 2: Observed and expected neutrino event rate.

3 Oscillation analysis

Oscillation analyses have been done based on χ^2 estimator. Uncertainties used for the oscillation analyses are summarized in Table 1. A ratio of observed-to-predicted events of 0.944 ± 0.016 (stat) ± 0.040 (syst) was observed, corresponding to $\sin^2 2\theta_{13} = 0.104 \pm 0.030$ (stat) ± 0.076 (syst) at $\Delta m_{13}^2 = 2.4 \times 10^{-3} \text{ eV}^2$. The analysis can be improved by using spectral information. The positron spectrum is divided into 18 variably sized energy bins from 0.7 MeV to 12.2 MeV. In order to introduce bin-to-bin correlations, we use four covariance matrices to include uncertainties on statistics, reactor, detector and background spectral shape. Shape difference between signal and background appears in the region from 8 to 12.2 MeV, reducing the uncertainties due to correlated backgrounds. Analyzing both the rate and their energy spectral shape, we found $\sin^2 2\theta_{13} = 0.086 \pm 0.041$ (stat) ± 0.030 (syst) with $\chi^2/\text{n.d.f.} = 23.7/17$. Observed and predicted positron energy spectra for no oscillation and the best-fit $\sin^2 2\theta_{13}$ including background are shown in Figure 3. No oscillation hypothesis is ruled out at the 94.6 % C.L., which can be interpreted as an indication of the non-zero θ_{13} . This result is compatible with follow-up results from the Daya Bay and RENO experiments. A combined analysis with the T2K and MINOS accelerator experiments on θ_{13} and CP violation phase δ vs θ_{13} plane for normal mass ordering is presented as shown in Figure 4.

4 Conclusion

Double Chooz started a search for the non-zero neutrino mixing angle θ_{13} using the new generation of $\bar{\nu}_e$ detector since April 2011. A ratio of observed-to-predicted events of 0.944 ± 0.016 (stat) ± 0.040 (syst) was observed in 101 days of detector running. We found $\sin^2 2\theta_{13} = 0.086 \pm 0.041$ (stat) ± 0.030 (syst) at $\Delta m_{atm}^2 = 2.4 \times 10^{-3} \text{ eV}^2$, based on rate and spectral shape information. The no oscillation hypothesis is excluded with 94.6 % C.L., which can be interpreted as an indication of the non-zero θ_{13} .

Table 1: Summary of uncertainties

Source		Uncertainty w.r.t signal	
Statistics		1.6 %	
Reactor	Bugey4 measurement	1.4 %	1.8 %
	Fuel composition	0.9 %	
	Thermal power	0.5 %	
	Reference spectra	0.5 %	
	Energy per fission	0.2 %	
	IBD cross section	0.2 %	
	Baseline	0.2 %	
Detector	Energy response	1.7 %	2.1 %
	E_{delay} containment	0.6 %	
	Gd fraction	0.6 %	
	Δt_{e+n}	0.5 %	
	Spill in/out	0.4 %	
	Trigger efficiency	0.4 %	
	Target H	0.3 %	
Background	Accidental	< 0.1 %	3.0 %
	Fast neutron	0.9 %	
	^9Li	2.8 %	

References

1. M. Apollonio *et al.* (CHOOZ Collaboration), *Eur. Phys. J. C* **27**, 331 (2003)
2. K. Abe *et al.* (T2K Collaboration), *Phys. Rev. Lett.* **107**, 041801 (2011).
3. P. Adamson *et al.* (MINOS Collaboration), *Phys. Rev. Lett.* **107**, 181802 (2011).
4. Y. Abe *et al.* (Double Chooz Collaboration), *Phys. Rev. Lett.* **108**, 131801 (2012).
5. F. P. An *et al.* (Daya Bay Collaboration), *Phys. Rev. Lett.* **108**, 171803 (2012).
6. J. K. Ahn *et al.* (RENO Collaboration), *Phys. Rev. Lett.* **108**, 191802 (2012).
7. P. Adamson *et al.* (MINOS Collaboration), *Phys. Rev. Lett.* **106**, 181801 (2011).
8. O. Meplan, Tech. Rep. LPSC 0912 and IPNO-09-01(2009).
9. R. R. G. Marleau and A. Hebert, Tech. Rep. IGE-157 (1994).
10. T. Mueller *et al.*, *Phys. Rev. C* **83**, 054615 (2011).
11. Y. Declais *et al.*, *Phys. Lett. B* **338**, 383 (1994).

Figure 3: Top: Observed and predicted positron energy spectra for the best-fit $\sin^2 2\theta_{13}$ and no-oscillation expectation with stacked background spectrum. Bottom: Difference between data and no-oscillation (dots) and difference between the best-fit $\sin^2 2\theta_{13}$ and no-oscillation expectation (line).

Figure 4: Combined analysis with Double Chooz, T2K and MINOS assuming normal mass ordering. The $\Delta\chi^2$ distribution for $\sin^2 2\theta_{13}$ (Upper plot) and the allowed region in δ vs $\sin^2 2\theta_{13}$ plane (Lower plot), respectively.