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Nuclear Physics B Proceedings Supplement 00 (2014) 1–3

Nuclear Physics B Proceedings Supplement

Measurement of the detection systematic uncertainty in the Double Chooz experiment

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Abstract

Double Chooz is a reactor antineutrino oscillation experiment designed to make a precision measurement of the neutrino mixing angle θ_{13}. The new methods developed for measuring the dominant components of the antineutrino detection systematic uncertainty using several neutron sources as well as the studies on the neutron transport boundary effects on the target are described. Benefiting from a revised signal selection criteria and increased statistics, the 0.5% precision level achieved on the detection systematic uncertainty represents almost a factor two improvement with respect to the previous result and leads to a more precise θ_{13} measurement. Building upon this improvement, the phase with two detectors will profit from an even better detection systematic uncertainty thanks to the cancellation of correlated uncertainties, granting a high precision θ_{13} measurement.

Keywords: efficiency, reactor, neutrino, oscillation, θ_{13}

1. The Double Chooz experiment

Double Chooz (DC) will measure the disappearance of $\overline{\nu}_e$ using two identical detectors located at $\sim$ 400 m (Near Detector) and 1050 m (Far Detector) from the two cores of the Chooz (France) nuclear power plant. The electron antineutrinos are detected through the inverse beta decay (IBD) process $\overline{\nu}_e + p \rightarrow e^+ + n$. A prompt signal is given by the positron energy deposit, followed by a delayed signal from the neutron capture in a gadolinium-loaded liquid scintillator target (NT).

In the first phase of the experiment (since April 2011), only the Far Detector (see figure 1) is operative, so the predicted $\overline{\nu}_e$ flux is derived from a Monte Carlo (MC) simulation.

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2. Detection systematic uncertainty

A MC normalization factor ensures the detection dependent accuracy of the simulation with respect to the data. The detection systematic uncertainty represents the uncertainty on this factor.

Source	MC norm.	Unc.
Number of protons (NT)	1.0000	0.30%
Active background rejection	0.9388	0.11%
Prompt signal selection	1.0000	negligible
Delayed signal selection	0.9750	0.54%
Total	0.9153	0.63%

Table 1: Inputs for the MC normalization correction factor and the detection systematic fractional uncertainty.

As seen in table 1, the delayed signal selection represents the dominant contribution to the uncertainty. This was already the dominant contribution in the previous DC result [1], amounting to 0.96%, and it has been re-

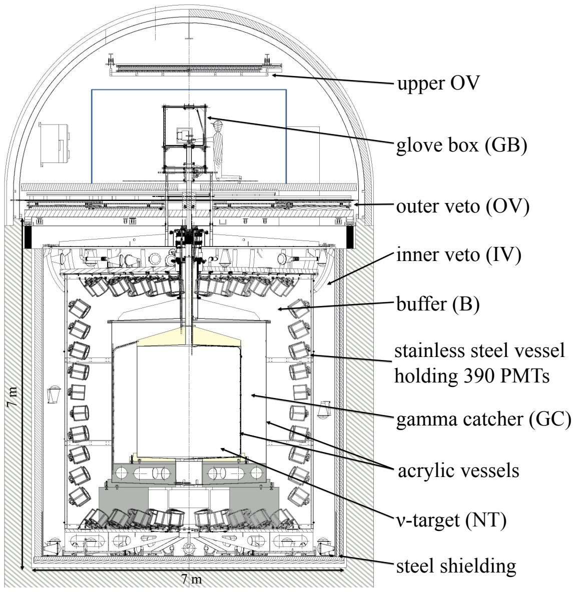

Figure 1: Double Chooz far detector design.

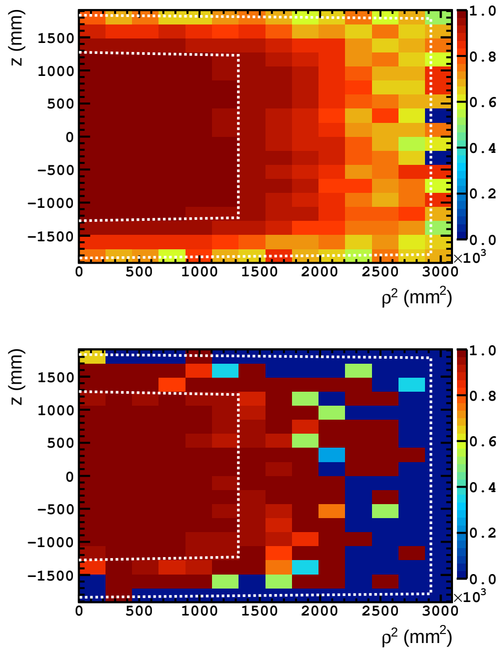

Figure 2: Efficiency maps for $\overline{\nu}_e$ MC (top) and IBD candidates with the accidental background subtracted (bottom). The dotted lines delimit the NT (inner) and the gamma-catcher volumes (outer).

duced to 0.54% for the latest result [2] using new methods described below. The MC normalization correction factor due to this source can be further decomposed into three contributions: a selection cut dependent factor (section 3), a factor related to the fraction of neutrons captured on Gd nuclei (section 4), and a neutron mobility factor (section 5). Thus, the delayed signal selection factor can be written as:

$$c_{delayed} \equiv c_{cut} \cdot c_{Gd} \cdot c_{spill} \quad (1)$$

3. Volume-wide selection systematic uncertainty

The correction factor arising from the IBD selection is computed as the ratio of the cut dependent efficiencies for data and MC. These efficiencies must be evaluated for the whole NT volume to include the reduction occurring close to the borders.

3.1. IBD measurement

The IBD events constitute a source of neutrons homogeneously distributed in the detector, so they are especially well-suited for a direct measurement of the volume-wide efficiency (see figure 2).

The numerator of the selection efficiency is given by the number of IBD events passing the delayed energy $(4 < E_{vis} < 10\,\text{MeV})$, correlation time $(\Delta T < 150\,\mu\text{s})$ and correlation distance $(\Delta R < 1\,\text{m})$ cuts for the oscillation analysis; while the denominator is given by the IBD events passing the extended cuts: $3.5 < E_{vis} < 10\,\text{MeV}$, $\Delta T < 200\,\mu\text{s}$, and $\Delta R < 1.7\,\text{m}$. The cuts are evaluated simultaneously to account for any possible correlation between them. In both cases, accidental background is subtracted using an off-time coincidence window. Integration over the NT volume yields a correction factor $c_{cut} = 0.9996 \pm 0.0021$ (stat + syst). The systematic uncertainty was estimated as the difference to the value of c_{cut} using only the bottom half of the NT to suppress the stopping muon background contamination. The result was proved to be stable against variations in the selection and efficiency definitions, and in the fiducial volume used in the integral. An exclusive definition of the efficiency, evaluating one cut at each time, provided a consistent result.

3.2. ^{252}Cf *measurement*

The ^{252}Cf is a high statistics fission source deployed along the NT symmetry axis during the calibration campaigns happening in the $\overline{\nu}_e$ data taking period. A clean selection is achieved by cutting in the prompt energy (fission γs), subtracting the accidental background with

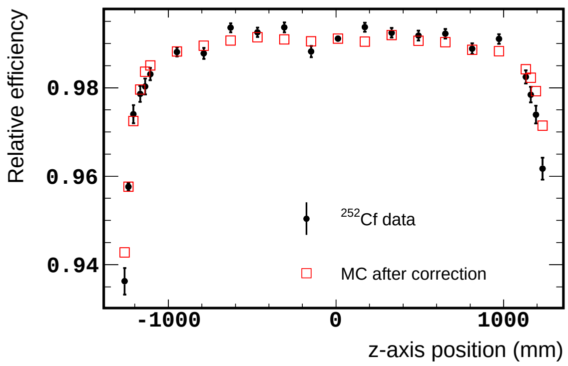

Figure 3: Efficiency as a function of the deployment position along the symmetry axis z. Black dots are data, red boxes are corrected MC.

an off-time selection and requiring a neutron multiplicity larger than 1. This allows to use wide cuts in the efficiency denominator: $3.5 < E_{vis} < 10\,\text{MeV}$, $\Delta T < 1000\,\mu\text{s}$, and no ΔR cut.

A volume-wide efficiency is computed by extrapolating the efficiencies from the deployed positions (see figure 3) to the full NT volume. This can be done since the behavior of the efficiency along the vertical coordinate, z, is the same as in the radial coordinate, ρ. The accuracy of this method was evaluated using the $\overline{\nu}_e$ MC . The correction factor is found to be $c_{cut} = 1.0003 \pm 0.0032\,(\text{stat} + \text{syst})$, where the dominant contribution to the uncertainty comes from the extrapolation to the full volume. Consistent results are found when using different calibration campaigns.

The final correction factor is computed by combining the results from the two sources: $c_{cut} = 1.0000 \pm 0.0019\,(\text{stat} + \text{syst})$.

4. Gadolinium-fraction systematic uncertainty

The gadolinium-fraction represents the proportion of radiative neutron captures that occur on Gd nuclei. It was measured using a ^{252}Cf source deployed at the center of the detector. It is estimated as the ratio of events in two delayed energy windows: $3.5 < E_{vis} < 10\,\text{MeV}$, which selects Gd captures, and $0.5 < E_{vis} < 10\,\text{MeV}$, which includes also the H captures. The correction factor is computed as the ratio of data to MC gadolinium-fraction, resulting in $c_{Gd} = 0.9750 \pm 0.0011\,(\text{stat}) \pm 0.0041\,(\text{syst})$, where the systematic uncertainty was estimated varying the integration energy window. Comparison with an earlier calibration shows that the correction factor is stable.

Furthermore, a crosscheck using IBD neutrons was performed, yielding a correction factor $c_{Gd} = 0.9794 \pm 0.0040\,(\text{stat}) \pm 0.0044\,(\text{syst})$, in agreement with the ^{252}Cf result. Another crosscheck was done using spallation neutrons produced by cosmic muons, finding an agreement within uncertainties.

5. Neutron migration systematic uncertainty

The NT acts as a fiducial volume in which the neutrons from the IBD events are captured on Gd nuclei. There is a normalization uncertainty due to neutron migration between detector volumes: neutrons created in the NT can escape and be captured on H outside (spill-out), while neutrons created outside the NT can be captured inside (spill-in). These two currents counterbalance, yet do not cancel out. Since the fraction of spill cannot be measured in the data, it is estimated using MC. This effect is sensitive to the low energy neutron physics modeling, especially to the molecular bonds of H to other atoms. The Geant4 simulation developed in DC includes an analytical modeling of the impact of molecular bonds on low energy neutrons. The uncertainty is given by comparing this simulation to another one using Tripoli4, known for the accurate modeling of low energy neutron physics, resulting in a correction factor $c_{spill} = 1.0000 \pm 0.0027$.

6. Outlook

The detection systematic uncertainty is currently dominated by the delayed signal contribution, specifically by the gadolinium-fraction and the neutron migration uncertainties. Both are originated in MC shortcomings to reproduce the data. However, this is a limitation restricted to the first phase of the experiment, in which data of only one detector must be compared to the MC; and it will be greatly reduced in the 2-detector phase, when only relative differences between the two detectors will be relevant. The fact that both detectors are built identical, including the scintillator mixture, allows to exploit maximally the uncertainty cancellation.

References

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