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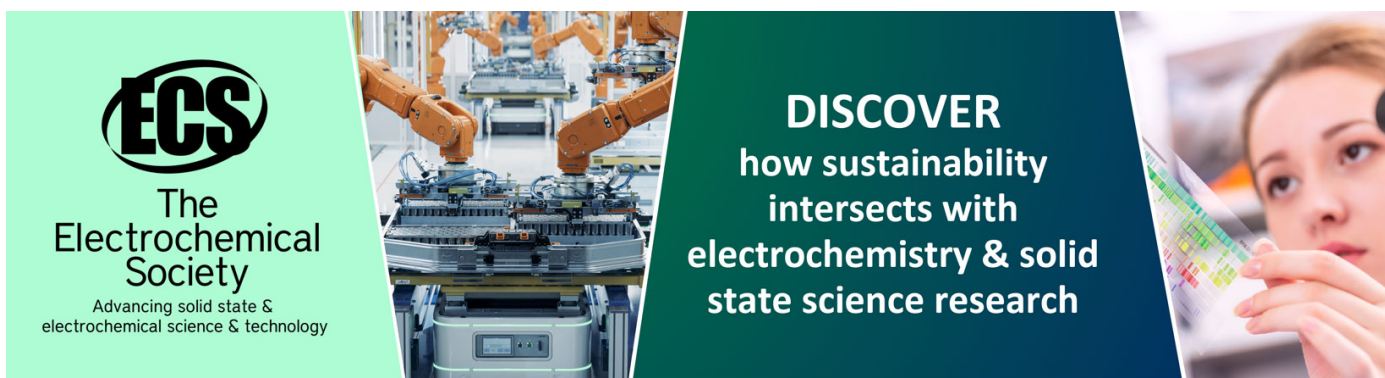
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Neutrino detection systematics in the two detector phase of the Double Chooz experiment

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Abstract. Being an intense and pure source of low energy electron antineutrinos, nuclear reactors are one of the most powerful tools to investigate neutrino oscillations. The Double Chooz experiment aims for a precise determination of the neutrino mixing angle θ_{13} using a two detector configuration with a liquid scintillator target volume read by photomultipliers.

The antineutrino detection efficiency systematic uncertainty is the dominant component in the normalization uncertainty affecting the final precision on the θ_{13} measurement. The collected data from the near detector since January 2015 will profit from improved detection systematic uncertainties thanks to the cancellation of correlated contributions between both detectors.

1. The Double Chooz Experiment

Double Chooz (DC) is a neutrino oscillation experiment which measures the disappearance of the electron antineutrinos produced in the nuclear power plant of Chooz, in order to obtain the mixing angle θ_{13} . For that, the experiment is based on a two detectors configuration. The first one (Near Detector) is located close to the reactor cores (~ 400 m) measuring the non-oscillating flux, and the other one (Far Detector) from a distance of almost 1km, is observing the oscillation around its maximum. Both detectors are made of different layers to optimize the electron antineutrino detection. The most inner volume, called neutrino-target (NT) is filled with Gadolinium (Gd) loaded liquid scintillator. And surrounding it, a Gd-free liquid scintillator named gamma-catcher (GC) is amplifying the emitted gammas in the neutrino interaction. These are detected by ~ 390 photomultipliers (PMTs) enclosing the GC volume with a non-scintillating mineral oil.

The Far detector is operative since April 2011 and in November 2011 DC presented the first measurement of θ_{13} , unknown until then [1]. This result is dominated by the uncertainty of the reactor neutrino flux. Since December 2014, the Near Detector is taking data, so this will allow to reduce this uncertainty and improve the precision of θ_{13} . In order to reach this goal, a high and accurately known detection efficiency of the electron antineutrino interaction, the inverse beta decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$, is required. The event signature consists of the coincidence of a prompt positron signal and a delayed neutron capture on Gd or Hydrogen (H) nuclei in the detectors liquid scintillators.



2. Detection Systematic Uncertainty

During the period of data taking with only one detector, the mixing angle θ_{13} is estimated from the comparison between data from the Far Detector and the Monte Carlo (MC) simulation of the antineutrino flux. Therefore it is needed to guarantee that the efficiency of both samples is properly determined [2]. Once the Near Detector is working, the relative difference between Far and Near detectors becomes a relevant parameter.

The most dominant uncertainty on neutrino signal detection is introduced by the detection efficiency of the neutron events. The neutron detection efficiency estimation is performed using two neutron sources. Firstly, the neutrons produced in the IBD give a homogenously distributed signal in the detector, being especially well-suited for a direct measurement of the global selection efficiency in the full target volume. Secondly, a ^{252}Cf fission source is deployed along the symmetry axis of the detector. This pointlike isotope emits neutrons at high multiplicity and allows to quantify the neutron capture fraction.

There are three main components that define the efficiency of neutron detection: the efficiency of the neutron selection cuts ε_{sel} (Section 2.1), the fraction of neutron captures in Gd or H $\varepsilon_{n\text{-captures}}$ (Section 2.2) and the neutron migrations around the different volumes of the detector ε_{spill} (Section 2.3).

The DC MC simulation is designed to replicate step by step the data, from the generation of the $\bar{\nu}_e$ in the reactor to their interaction in the detectors. However, in order to make the simulation output comparable to the actual data, ε^{DATA} , ε^{MC} must be corrected to account for known effects that have not been included in the simulation. This is achieved using a MC normalization correction factor defined as $c_{MC} \equiv \frac{\varepsilon^{DATA}}{\varepsilon^{MC}}$.

Analogously it is needed to account for the uncorrelated uncertainties between the two detectors. In this case, the normalization correction factor is defined as $c_{DATA} \equiv \frac{\varepsilon^{DATA-FD}}{\varepsilon^{DATA-ND}}$

2.1. Neutron selection efficiency

The neutron selection efficiency, ε_{sel} , corresponds to the overall efficiency of the delayed energy, correlation time and distance cuts used to select the neutrons produced in the IBD reaction. The IBD events occur in all the detector, so the neutrons produced are especially well-suited for a direct measurement of the volume-wide efficiency.

The numerator of the selection efficiency is given by the number of IBD passing the delayed energy ($4 < E_{vis} < 10$ MeV), correlation time between prompt and delayed signal ($0.5 < \Delta T < 150$ μs) and correlation distance ($\Delta R < 1$ m) cuts for the oscillation analysis; while the denominator corresponds to a larger number of events which satisfy a looser version of the cuts: $3.5 < E_{vis} < 10$ MeV, $0.5 < \Delta T < 800$ μs and $\Delta R < 1.2$ m.

In this analysis accidental coincidences of the natural background radiation are the main background source. Using an off-time coincidence window, this background is measured with high precision and it can be subtracted with negligible statistical uncertainty.

2.2. Neutron capture efficiency

The $\varepsilon_{n\text{-capture}}$ estimates the fraction of neutron captures occurring in the liquid scintillator forming the detector target. The neutron capture is a competitive process between the different isotopes in the detector liquid scintillator. It depends on the neutron capture cross-section and

the abundance of the isotopes present in the medium. In the NT, this competitive process is mainly taking place between the Gd and the H nuclei in the organic scintillator (more than a 99% of the neutrons are captured on any of them). The neutrons captured by Gd-nuclei release a gamma of around 8 MeV, where the H captures generate gammas with a total 2.2 MeV energy.

Considering these capture energies, it is possible to define a Gd-neutron capture efficiency as $\varepsilon_{\text{Gd}} = N_{\text{Gd}} / (N_{\text{Gd}} + N_{\text{H}})$, where N_{Gd} is the number of events in the energy region [3.5, 10] MeV and N_{H} with energies [1.3, 3.5] MeV. On that way, the neutron capture spectra is divided between neutron captures on Gd- and H-nuclei, $\varepsilon_{\text{Gd}} = 1 - \varepsilon_{\text{H}}$. The measurement of the Gd-neutron capture fraction is obtained using ^{252}Cf neutrons at the NT center.

2.3. Neutron migration systematic uncertainty

The NT volume acts as the fiducial volume for the IBD selection using neutron captures on Gd-nuclei. The energy dependence in the neutron capture cross sections causes that neutrons need to slow down until they can be captured in the detector. When an IBD neutron is captured on a different volume where it was created, the so called *spill event* appears. It can occur for neutrons produced in the NT and captured in the GC (spill-out), and for IBD processes on the GC where the neutron is captured in the NT (spill-in). These events do not cancel out, and need to be evaluated in the neutron detection efficiency. This term $\varepsilon_{\text{spill}}$ is evaluated with a low energy neutron physics modelling, developed with a Monte Carlo simulation.

3. Conclusion

The detection systematic uncertainty is currently dominated by the delayed signal contribution, that is, the neutron detection efficiency. The estimation of this efficiency and its correction factor has been described. The neutron selection efficiency, the neutron captures fraction and the spill-in/out components which constitute this efficiency have been presented in dedicated subsections. The first two components are studied using two neutron sources, electron antineutrinos and the ^{252}Cf , while the neutron currents are measured using the MC $\bar{\nu}_e$ simulation.

In the one detector phase, Double Chooz relies on a MC simulation to predict the $\bar{\nu}_e$ flux at the Far Detector which is compared to data to measure the oscillation-induced deficit. Therefore, the accuracy of the efficiency of both samples, data and MC is mandatory in this phase of the experiment.

In the two-detector phase, only the uncorrelated uncertainties between detectors will affect the precision of the $\sin^2(2\theta_{13})$ measurement. Since the two detectors have been made identical, the uncertainty caused by the fraction of neutron captures and the spill current cancel almost completely. Hence the major contribution to the uncertainty is the neutron selection efficiency; however it will be reduced as more antineutrino data are taken with both detectors.

References

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- [2] Abe Y *et al.* 2014 Improved measurements of the neutrino mixing angle 13 with the Double Chooz detector *JHEP* **10** 086