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Reactor spectral rate and shape measurement in Double Chooz detectors

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Abstract. Since 2015, the neutrino oscillation reactor-based experiment Double Chooz (DC) is taking data with its near and far detectors. Commissioning of the near detector, weakly affected by the θ_{13} driven oscillation, allows DC to perform a precise measurement of the rate and shape of the reactor induced $\bar{\nu}_e$. Here, we report the preliminary reactor shape results for both detectors and the prospective sensitivity to the reactor mean cross-section per fission for the near detector.

1. Introduction

Recently, a new generation of reactor-based neutrino experiments aiming to measure the θ_{13} mixing angle characterizing the neutrino oscillation phenomena was developed [1, 2, 3]. For this purpose, the Double Chooz experiment is looking for a disappearance of the $\bar{\nu}_e$ emitted by the two 4.25 GWth Pressurized Water Reactor cores (PWR) of the Chooz power plant in the French Ardennes. $\bar{\nu}_e$ are detected through inverse beta decay reaction (IBD) in two identical detectors respectively installed at ~ 400 m and ~ 1050 m from the reactors. The IBD signature is a coincidence of a prompt positron signal followed by a delayed neutron capture induced by the interaction of $\bar{\nu}_e$ with a free proton in a liquid scintillator doped with gadolinium.

For the first phase of the experiment, in which only the far detector was taking data, Double Chooz reported in 2015 a distortion above 4 MeV in the observed IBD spectrum compared to the prediction [1]. This deviation, also reported later on by Reno and DayaBay experiments cannot be explained by the θ_{13} driven oscillation or an unknown background. At the same time, Double Chooz completed the construction of the near detector allowing a more precise measurement of reactor antineutrino flux emitted by the cores.

Recently, a new analysis based on both gadolinium and hydrogen capture of delayed events (IBD[Gd+H] analysis) was developed. This new analysis takes advantage of the high number of protons available in the detectors. This new analysis leads to an overall increase of the measured IBD candidates by a factor of 2.4. Analysing 15 months of data, DC measured respectively $\sim 200\,000$ and $\sim 40\,000$ IBD candidates in the near and the far detectors.



2. Expected antineutrino rate

The expected number of $\bar{\nu}_e$ IBD interactions in the Double Chooz detectors is calculated by a Monte Carlo (MC) simulation composed of both $\bar{\nu}_e$ IBD interaction and detector response.

The thermal power of PWR's and subsequent antineutrino flux is mainly induced by the fission of the four isotopes: ^{235}U , ^{238}U , ^{239}Pu and ^{241}Pu . In the non-oscillation hypothesis, the antineutrino flux in any DC detectors can be expressed as:

$$N_{\nu}^{exp}(s^{-1}) = \frac{N_p \epsilon}{4\pi} \sum_{r=B_1, B_2} \frac{1}{L_r^2} \frac{\langle P_{th} \rangle_r}{\langle E_f \rangle_r} \langle \sigma_f \rangle_r \quad (1)$$

where N_p is the number of target protons, ϵ the detector efficiency, L_r the distance of the reactor r to the detector, $\langle P_{th,r} \rangle$ the average thermal power of reactor r , $\langle E_f \rangle_r$ the mean energy released per fission in the reactor r and $\langle \sigma_f \rangle_r$ the mean cross-section per fission in the reactor r defined as:

$$\langle \sigma_f \rangle = \sum_k \alpha_k \langle \sigma_f \rangle_k = \sum_k \alpha_k \int_0^\infty dE S_k(E) \sigma_{IBD}(E) \quad (2)$$

with α_k the fraction of fissions of the k^{th} fissioning isotope, $S_k(E)$ the reference antineutrino spectrum of the k^{th} isotope and $\sigma_{IBD}(E)$ the IBD cross-section.

α_k of Chooz reactors are estimated through a dedicated reactor simulation using the MURE package [5]. In DC, re-evaluations of the ILL reference antineutrino spectra are used for ^{235}U , ^{239}Pu , ^{241}Pu isotopes [6, 7]. For ^{238}U , the antineutrino spectrum derived from the FRM-II measurement is used [8]. Off-equilibrium effects from [7] are also taken into account. In order to reduce the uncertainties coming from the reference antineutrino spectra and to cancel possible neutrino oscillation at very short baseline due to heavy $\Delta m^2 \sim 1\text{eV}^2$ sterile neutrinos, the Bugey4 measurement [9] is used as an anchor point for the mean cross-section per fission $\langle \sigma_f \rangle$. The Bugey4 measurement was performed in the 80's at 14m from a PWR. With a relative uncertainty of 1.4%, it is up to now the most precise available measurement.

3. Reactor rate and shape measurement

At the time of writing, DC performed a preliminary analysis of the reactor spectral shape measurement in the near and far detectors for the new IBD[Gd+H] analysis. Comparison of the oscillated IBD prediction with measurements is presented in Figure 1 for both detectors for the IBD[Gd+H] analysis. The MC prediction is based on method presented in section 2, and corrected for θ_{13} oscillation using the value previously presented in [4]. The background model and energy scale prior to the θ_{13} fit are used in these plots. A better constraint on both of these parameters is expected after the θ_{13} fit. Nevertheless, both analyses exhibit the same distortion pattern between data and prediction in the [4;6] MeV range than the one previously observed with the far detector. Underestimation of the uncertainty on reference antineutrino spectra is the most favoured hypothesis of the observed distortion. Recently, the dependence of this distortion with the reactor fuel composition was investigated in [10] taking advantage of several experiments exhibiting different fuel composition during the period of data taking. Because of the simple configuration with only two reactors, DC is expected to collect data for different average reactor fuel compositions, helping then to investigate more precisely this distortion. High statistics will be a key parameter for such an analysis.

In addition to the reactor shape analysis, DC will be able in the near future to provide a precise measurement of reactor $\bar{\nu}_e$ rate in an IBD detector. A projection of the mean cross-section per fission sensitivity in the near detector for both IBD[Gd] and IBD[Gd+H] analyses is presented in Figure 2 for the near detector. As for the shape analysis, the background model and energy scale prior to the θ_{13} fit are used for this projection. The main difference between IBD[Gd] and IBD[Gd+H] analyses comes from the lower statistical uncertainty for the latter. With such sensitivity, DC will be able to reach the sensitivity of the best available measurements.

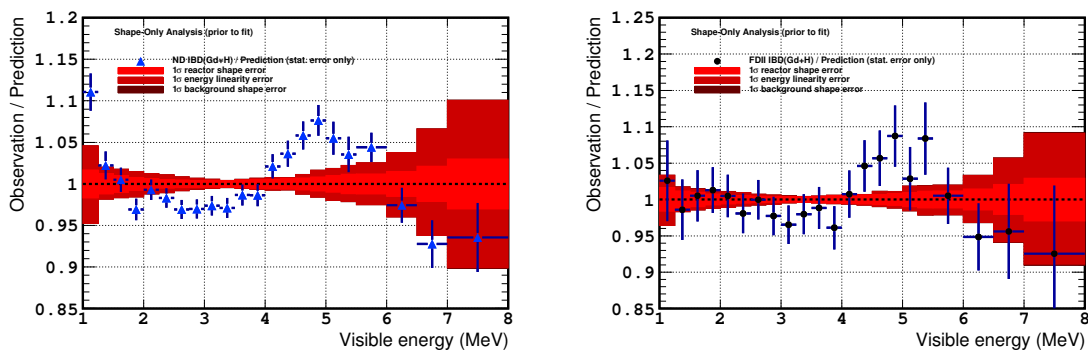


Figure 1: Ratio of the IBD[Gd+H] data to the oscillated flux prediction with background model and scaled to the data for the near (left) and far (right) detector.

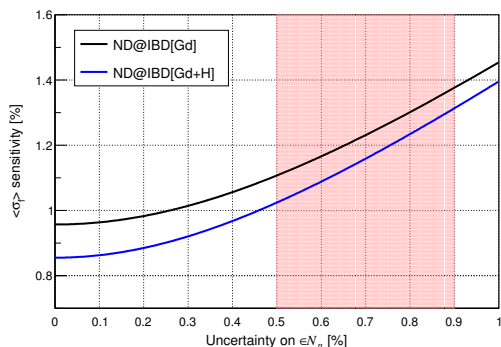


Figure 2: DC sensitivity on the reactor $\bar{\nu}_e$ IBD mean cross-section per fission with the near detector for the IBD[Gd] and IBD[Gd+H] analyses as a function of the uncertainty on the product of proton number (N_p) and detection efficiency (ϵ). Red bands correspond to the expected range of sensitivity for the 15 month of data analysed with both detectors running.

4. Conclusion

At the Neutrino 2016 conference, the Double Chooz experiment presented its new IBD[Gd+H] analysis. Thanks to it, arose an important increase in the number of measured IBD candidates. In this proceeding we reported the first preliminary results of a reactor shape analysis for both detectors. A projection of mean cross-section per fission sensitivity expected with the near detector data was also presented. Based on the reactor and detector response systematics computed for the previous analysis, DC is expected in the near future to measure the absolute rate of reactor $\bar{\nu}_e$ IBD events with a precision at the level of the Bugey4 measurement.

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