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Reactor and Antineutrino Spectrum Calculations for the Double Chooz First Phase Results

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The Double Chooz reactor oscillation experiment is designed to search for a non-vanishing value of the mixing angle θ_{13}. For the first phase of the experiment with only the far detector running, the reactor electron antineutrino flux is normalized via reactor simulation. For this first phase and from its last results, Double Chooz observed an evidence for a reactor electron antineutrino disappearance. In 227.93 days of far detector live time, we obtained $\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat) $\pm$ 0.025 (syst). This result excludes the no-oscillation hypothesis at 99.8% CL.

I. INTRODUCTION

Up to very recently, the θ_{13} mixing angle remained the last unknown parameter governing neutrino oscillation properties. From the first Chooz reactor experiment, only an upper limit was known: $\sin^2 2\theta_{13} < 0.14$ [1]. In 2011, the accelerator experiments T2K [2] and MINOS [3] reported indications for a non-zero value of θ_{13}. These results were followed in the fall of 2011 by that of Double Chooz [4], the first reactor experiment to report such an indication and then by those of two other reactor experiments, Reno [5] and Daya Bay [6], that observed a reactor antineutrino disappearance.

The search for the θ_{13} parameter with a short baseline reactor experiment can be done within a two flavor oscillation scheme according to the $\bar{\nu}_e$ survival probability formula

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{(1.27\Delta m^2_{31} L)}{E_{\bar{\nu}_e}}, \quad (1)$$

where Δm^2_{31} is the difference of the squared masses in eV^2 from the MINOS experiment, L the distance between the reactor and the detector in meters and $E_{\bar{\nu}_e}$ the energy of the antineutrino in MeV.

The Double Chooz experiment takes place in the French Ardennes in the Chooz nuclear power plant of the EDF company (Electricité de France), consisting of two identical pressurized water reactors (PWR N4-type) of nominal power 4.25 GW_{th}. Two detectors will be installed on the site. A near detector located at 400 m, used to normalize the antineutrino flux emitted by the cores, and a far detector at about 1050 m that observes the oscillated antineutrino flux. Double Chooz is currently in its first phase during which only the far detector is running since April 2011. The reactor flux normalization is thus computed through reactor simulations of the Chooz reactor cores. All the results presented here correspond to the latest Double Chooz results coming from Ref. [7].

II. ANTINEUTRINO DETECTION

The antineutrinos are detected in a ν-target (NT) of about 10.3 m^3 of scintillator doped with gadolinium through the inverse beta decay reaction (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$ (threshold 1.8 MeV). The signal then consists of a time coincidence between a prompt event characterized by photons from ionization and annihilation of the positron in the scintillator (1-8 MeV) and a delayed event resulting from the gamma emission after the neutron capture on gadolinium after thermalization (~8 MeV). An average time of about 30 μs between the prompt and the delayed signals is expected. The $\bar{\nu}_e$ energy can be reconstructed from the prompt signal as $E_{prompt} = E_{\bar{\nu}_e} - T_n - 0.8$ MeV where T_n is the average neutron recoil energy.

The detector consists of four concentric cylindrical tanks. The NT is surrounded by a γ-catcher of pure scintillator aiming to increase detection efficiency by catching gamma rays escaping from the target. The NT and the γ-catcher constitute the inner detector (ID) and are viewed by 390 PMTs immersed in a buffer volume filled with mineral oil in order to reduce radioactivity coming from PMTs. An inner veto (IV) and an outer veto (OV) respectively take place around and at the top of the buffer aiming to tag the cosmic muon. The detector is protected from background radioactivity by steel shielding.

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III. ANTINEUTRINO SELECTION

The $\bar{\nu}_e$ selection starts with a rejection of candidates with an energy below 0.5 MeV (trigger efficiency lower than 100%) or if candidates are identified as PMT light noise ($Q_{max}/Q_{tot} > 0.09$ or $rms(t_{start}) > 40$ ns where Q_{max}, Q_{tot} and $rms(tstart)$ are respectively the total charge collected by the PMTs, the maximum charge recorded by a single PMT and the standard deviation of the times of the first pulse on each PMT). $\bar{\nu}_e$ candidates in the far detector are then selected from the IBD via the following cuts applied on obtained data:

- 0.7 MeV $< E_{prompt} <$ 12.2 MeV;
- 6.0 MeV $< E_{delayed} <$ 12.0 MeV and $Q_{max}/Q_{tot} <$ 0.055;
- time difference between prompt and delayed events: 2 μs $< \Delta T <$ 100 μs;
- multiplicity cut to reject correlated backgrounds: no additional triggers from 100 μs preceding the prompt signal to 400 μs after it;
- high-energy muons: rejection of candidates within a 0.5 s window after a high energy muon ($E_{\mu}^{vis} >$ 600 MeV), tagged as cosmogenic isotope events.
- rejection of candidates whose prompt signal is coincident with an OV trigger, tagged as correlated background.

Applying the above cuts and with the far detector live time of 227.93 days, 8249 $\bar{\nu}_e$ candidates were selected corresponding to a rate of 36.2 ± 0.4 events/day.

In addition, the different background sources have to be estimated. Three types of backgrounds can occur: accidental, cosmogenic and correlated background.

The accidental background is induced by the coincidence of two uncorrelated signals that mimic the prompt and the delayed signals. A prompt-like signal is due to natural radioactivity and a delayed-like signal is due to a cosmic muon creating a neutron by spallation which is then thermalized in the detector. This background is estimated to be 0.261 ± 0.002 events/day.

The cosmogenic isotopes ^{9}Li and ^{8}He, which are β-n emitters, are produced by cosmic muon spallation on ^{12}C in the liquid scintillator. Their decay energy and later the neutron capture on gadolinium produce two temporally and spatially correlated events which can mimic the $\bar{\nu}_e$ signal. Using a veto time after high-energy muons, the cosmogenics rate is found to be 1.25 ± 0.54 events/day.

The correlated background has two contributions: Fast Neutrons (FN) and Stopping Muons (SM). FN are created by muons interacting in the rock surrounding the detector. Some of them happen to be slowed down and captured in the scintillator. The recoil proton can mimic the positron and the neutron capture shows temporal and spatial correlation similar to a $\bar{\nu}_e$ event. SM are created by a low energy muon entering into the detector through the chimney and decaying. The muon energy lost by ionization in the ID mimics the prompt event and the Michel electron upon the muon decay mimics the delayed event. The total rate of correlated background is estimated to be 0.67 ± 0.20 events/day.

IV. EXPECTED ANTINEUTRINO RATE

In PWRs, the thermal power is mainly induced by the fissions of the four nuclei: ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu. Reactor $\bar{\nu}_e$ are then produced when fission fragments β^- decay back to stability. The expected detected $\bar{\nu}_e$ flux in the hypothesis of $\theta_{13} = 0$ in the far detector for a considered period of time can be expressed as

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

where N_p is the number of target protons, ϵ the detector efficiency, L_r the distance of the reactor r to the detector, $\langle P_{th} \rangle_r$ 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. B1 and B2 stand for the two cores of the plants.

For each given reactor, the mean energy released per fission is computed as: $\langle E_f \rangle = \sum_k \alpha_k \langle E_f \rangle_k$ where the α_k and $\langle E_f \rangle_k$ are respectively the fission fraction and the mean energy released per fission of the k^{th} isotope ($k =^{235}$U, ^{238}U, ^{239}Pu, ^{241}Pu). Fission fraction and associated errors are evaluated using two simulation codes: MURE and DRAGON [8, 9] (see Section V). The $\langle E_f \rangle_k$ values are taken from Ref. [10]. The thermal power of the core is provided by EDF and is evaluated over time steps of $<$ 1 minute. A detailed study of this measurement was performed by EDF and the error at the nominal full power is 0.5 % (1σ C.L.). This error is considered fully correlated between the two cores.

For each given reactor, the mean cross-section per fission is defined as

$$\langle \sigma_f \rangle = \sum_k \alpha_k \int_0^{\infty} dE S_k(E) \sigma_{IBD}(E), \quad (3)$$

where $S_k(E)$ is the reference $\bar{\nu}_e$ spectrum of the k^{th} isotope and $\sigma_{IBD}(E)$ the IBD cross-section.

In order to reduce the uncertainties coming from the reference spectra and to cancel possible neutrino oscillation at very short baseline due to heavy $\Delta m^2 \sim 1$ eV^2 sterile neutrinos, the Bugey4 measurement [11] is used as an anchor point for the mean cross-section per fission. The mean cross-section per fission can be expressed as a function of Bugey4 measurement as

$$\langle \sigma_f \rangle_r = \langle \sigma_f \rangle^{Bugey} + \sum_k (\alpha_k^r - \alpha_k^{Bugey}) \langle \sigma_f \rangle_k. \quad (4)$$

The second term is a correction to take into account that inventories and therefore fission fractions of Bugey4 experiment and Double Chooz are not the same during the period of data taking. Recent re-evaluation of