Residual reactor antineutrinos observation with the Double Chooz detectors

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On behalf of the Double Chooz collaboration

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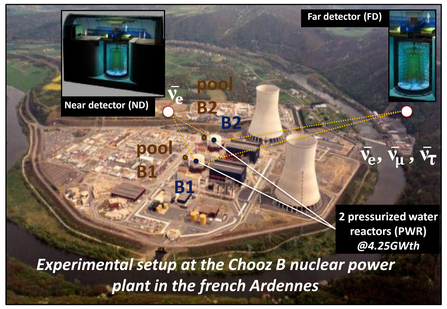
The Double Chooz experiment 1

- Designed to measure the θ_{13} mixing angle using reactor $\bar{\nu}_e$ with two identical liquid scintillator detectors: near detector (ND) and far detector (FD)
- Pure $\bar{\nu}_e$ source: β^- decay of fission products in nuclear fuel from fission of **^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu**



Experimental setup at the Chooz B nuclear power plant in the french Ardennes

Simple site configuration: **- 2 reactors - 2 detectors**

	Near [m]	Far [m]
Reactor B1	469	1114
Reactor B2	355	998

$\bar{\phi}_{\bar{\nu}_e}: \sim 8.10^{20}\ \bar{\nu}_e/s$

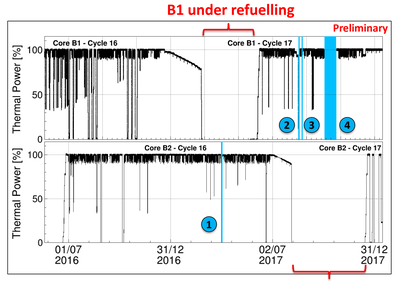
θ_{13} obtained by contrasting observed IBD rate+shape spectral distortion in ND & FD against the specific neutrino oscillation model prediction

➡ **Last Double Chooz results: $\sin^2(2\theta_{13}) = 0.105 \pm 0.014$**

(Nature Phys. 16 (2020) 5, 558-564)

Reactor Off periods 2

4 periods in 2017 with both reactors off and both detectors taking data



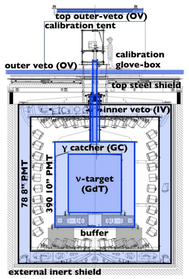
- Periods with both reactors off
  - 1: ~37 h (B2 off / B1 under refuelling)
  - 2: ~26 h (B1 off / B2 under refuelling)
  - 3: ~24 h (B1 off / B2 under refuelling)
  - 4: ~500 h (B1 off / B2 under refuelling)
- High duty cycle during reactors off periods
  - **ND: 563.0 h (ε = 96%)**
  - **FD: 555.0 h (ε = 95%)**

➡ **Rare opportunity to measure background and residual $\bar{\nu}_e$ (from β^- emitters accumulated in the nuclear fuel when the reactors are on) with both reactors off**

Unique feature of DC in the current reactor experiment landscape thanks to its simple site configuration with only two reactors

$\bar{\nu}_e$ detection & IBD candidate selection 3

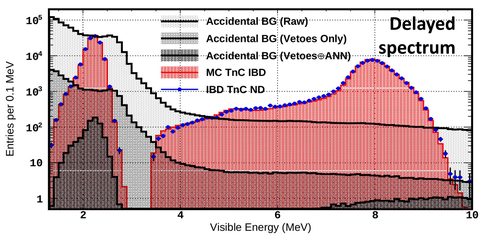
Detection of $\bar{\nu}_e$ through inverse beta decay reaction (IBD)



*ν*Target : scintillator doped with Gd
γ-catcher: undoped scintillator

- E_{Thr}: 1.8 MeV
- $\langle\sigma\rangle \sim 10^{-43}\mathrm{cm}^2$

$\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt / delayed) ↕ coincidence!



New Total neutron Capture (TnC) analysis: IBD acceptance criteria opened to integrate over all capture-γ's: ~2.2 MeV (H-n), ~5.0 MeV (C-n) and ~8 MeV (Gd-n) in all volumes.

➡ **High statistic boost (x2.5) compared to previous analysis (Gd-n only)**

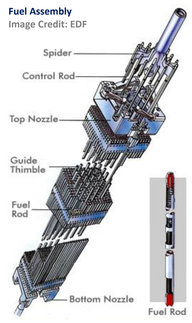
Residual reactor $\bar{\nu}_e$ 4

Reactor fuel:

- 205 UO_2 fuel assemblies in each core
- assemblies irradiated for 3 cycles (~15 GW.days/ton per cycle)
- 1/3 of assemblies discharged and moved in the pools for cooling about every 12 months

Residual $\bar{\nu}_e$ flux

During a reactors off period, residual $\bar{\nu}_e$ from 3 contributors:
- assemblies under cooling in the pool of each cores
- assemblies in the reactor that just shutdown
- assemblies in the reactor under refuelling and kept for the next cycle.

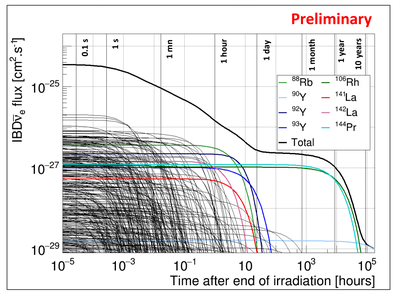


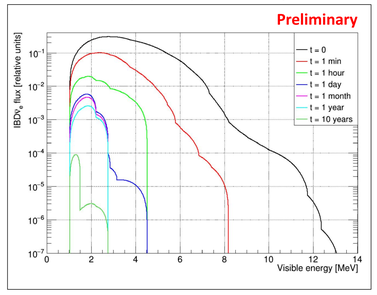
Reactor simulation work ongoing to model residual $\bar{\nu}_e$ emission of each contributor during each reactors off period through coupling of β^- emitter activity prediction with $\bar{\nu}_e$ spectra library

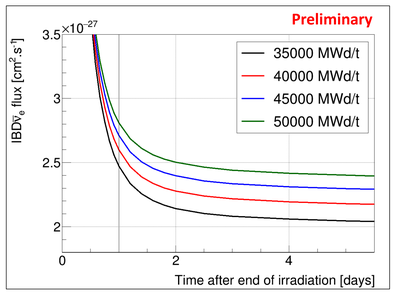
2 independent models under developpement:
- simplified reactor model (Campaign3_3) and $\bar{\nu}_e$ library using nuclear data from IAEA database
- reactor simulation codes APOLLO2 and DARWIN3 with $\bar{\nu}_e$ library BESTIOLE

Typical $\mathrm{IBD}_{\bar{\nu}_e}$ rate & spectrum during a cooling

Study for a reference case of an assembly with an initial 4% enrichment in ^{235}U and assuming an irradiation of 45 GW.days/ton (typical burnup reach after 3 irradiation cycles in a Chooz core)







After few hours:
- only 8 isotopes (^{88}Rb, ^{90,92,93}Y, ^{106}Rh, ^{141,142}La, ^{144}Pr) contribute to more than 90% of the total $\mathrm{IBD}_{\bar{\nu}_e}$ flux
- $\mathrm{IBD}_{\bar{\nu}_e}$ rate decreases by more than 2 orders of magnitude
- spectrum restrained to the low energy

0h	1h	6h	12h	24h
47	81	90	97	>99

Table: % of spectrum < 3 MeV (visible energy)

Background & reactor off data 5

Two types of background expected

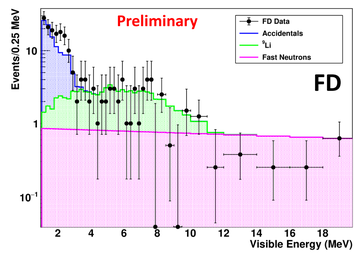
- **Accidental coincidence**
  γ + spallation n
- **Correlated coincidence**
  - Fast neutron:
    n + p → p + n
  - Stopping muon:
    μ → e⁻ + ν + ν
  - Cosmogenic β-n emitter:
    ^{9}Li → α + α + e⁻ + ν + n

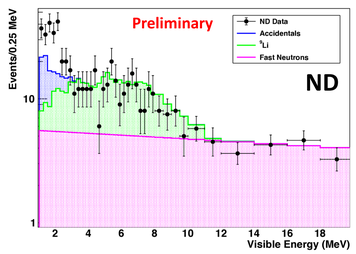
Prompt mimic — Delayed mimic

	FD	ND
IBD candidates	**210** (σ_{stat} = 7%)	**710** (σ_{stat} = 4%)
IBD candidates - Σback.	**25 ± 15**	**101 ± 35**
Background rate [d^{-1}]		
• **Accidental**	4.13 ± 0.02	3.110 ± 0.004
• **Fast-Neutron**	2.5 ± 0.05	20.85 ± 0.31
• **^{9}Li**	2.62 ± 0.27	14.52 ± 1.48
• **Stopped-μ**	<0.19 @ 98%CL	<0.21 @ 98%CL
• **Others (12B, BiPo)**	<0.01	0.04 ± 0.01

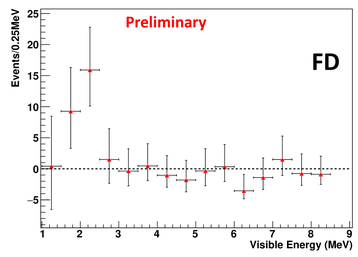
IBD candidates and background rates in the 1-20 MeV energy range during all reactors off periods combined (**Preliminary**).

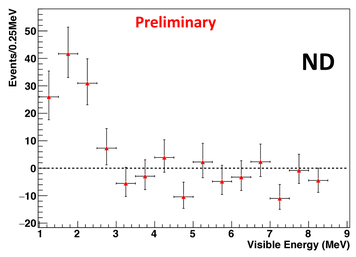
Reactors off data





Reactors off data – background substracted





➡ **After background substraction:**
- **E > 3 MeV: residual compatible with 0. Validation of the rate & shape of the background**
- **E < 3MeV: excess of events consistent with residual reactor $\bar{\nu}_e$**

Conclusion 6

Preliminary analysis of ~24.5 days with both reactors off in 2017 ⇒ unique feature of Double Chooz thanks to its simple site configuration

- **210 IBD candidates in ND**
- **710 IBD candidates in FD**

after background substraction ➡ **25 ± 15 residual $\mathrm{IBD}_{\bar{\nu}_e}$ candidates** / **101 ± 35 residual $\mathrm{IBD}_{\bar{\nu}_e}$ candidates**

➡ **Observed spectrum in very good agreement with the background measurement and shape of residual spectral consistent with expected spectrum from residual**

↳ Next step: precise comparison between Data and Prediction (on-going)