ORTHO-POSITRONIUM OBSERVATION IN THE DOUBLE CHOOZ EXPERIMENT

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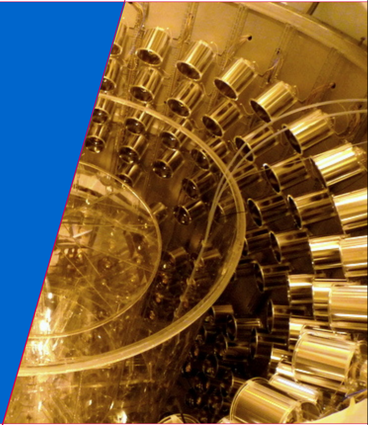

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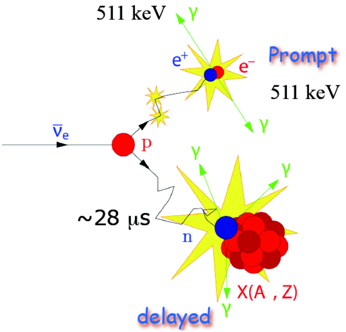
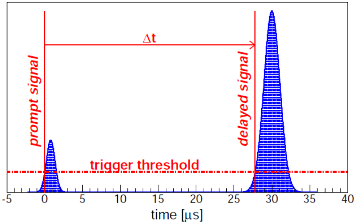
Neutrino detection with DC detector

- Detection of reactor $\bar{\nu_e}$ in liquid scintillator (PXE+PPO)

- **Signal :**
  - Inverse Beta Decay (IBD) : $\bar{\nu_e} + p \rightarrow e^+ + n$
  - Prompt from e^+ annihilation
  - Delayed from neutron capture (Gd, H)

- **Background :**
  - Accidentals :
    - Radioactivity γs
    - Spallation neutrons
  - Correlated :
    - Stopping muons
    - Fast neutrons
    - Cosmogenic Beta-n-emitting isotopes (9Li, 8He)

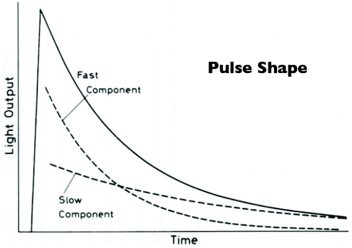




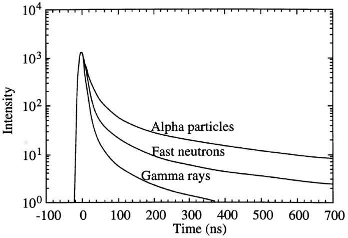
Pulse shape in liquid scintillator

- Global waveform profile of the scintillation light :
  - Initial rise (A_1, τ_1)
  - Two components fall : fast (A_2, τ_2) and slow (A_3, τ_3)

Scintillator	τ_1 [ns]	τ_2 [ns]	τ_3 [ns]
PC + 1.5 g/l PPO	3.57	17.6	59.9
PXE + 1.5 g/l PPO	3.16	7.70	34.0
LAB + 1.5 g/l PPO	7.46	22.3	115.0



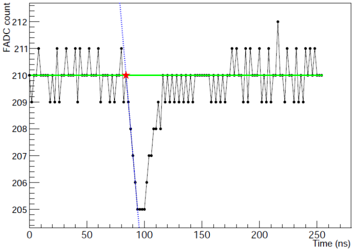
- dE/dx dependency :
  - higher slow component amplitude for heavy particles
  - Discrimination using $Q_{\text{tail}}/Q_{\text{total}}$ or Gatti method

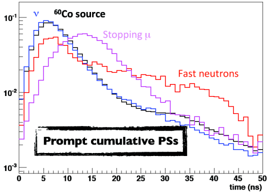


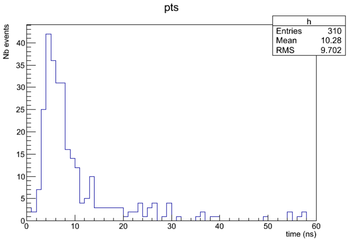
Pulse shape reconstruction in DC

- **Pulse shape** (PS) = Time distribution of PMT signal

- Linear fit to get the starting time
- TOF from the reconstructed vertex and PMT transit time corrections
- Distribution of all PMT starting times for an event
- Cumulative PS :
  Sum of distributions for all selected events

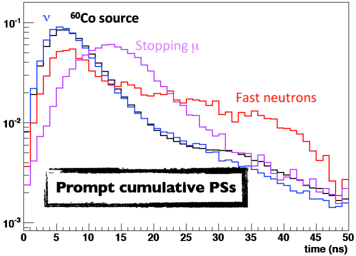


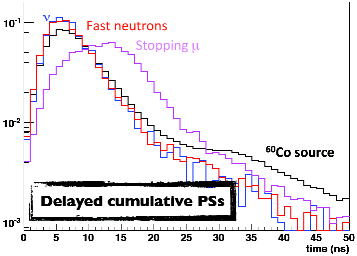




Correlated background reduction in DC

- **Neutrinos :**
  - prompt : e^+
  - delayed : Gd γs
- **Fast neutrons :**
  - prompt : recoil $p \rightarrow \neq$ PS
  - delayed : Gd γs $\rightarrow$ same PS
- **Stopping μ :**
  - prompt : $\mu \rightarrow \neq$ PS
  - delayed : Michel e^- but $\neq$ PS $\rightarrow$ due to vertex reconstruction fail for events occurring in the chimney upper the detector
- **Beta-n-emitting isotopes :**
  - ex : ${}^9Li \rightarrow {}^8Be + n + e^-$
  - prompt : e^- $\rightarrow$ same PS
  - delayed : Gd γs $\rightarrow$ same PS
  - Require e^-/e^+ discrimination

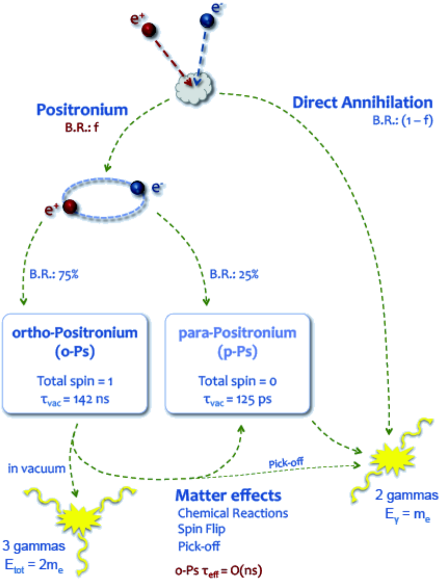




- **Electron/Positron :**
  - Direct annihilation
  - Metastable bound state
    $\rightarrow$ Positronium

- 2 possible configurations :
  - para-Positronium (p-Ps)
    (BR : 25%, spin 0)
  - ortho-Positronium (o-Ps)
    (BR : 75%, spin 1)
- Matter effects :
  $\rightarrow$ Reduce o-Ps lifetime to a few ns

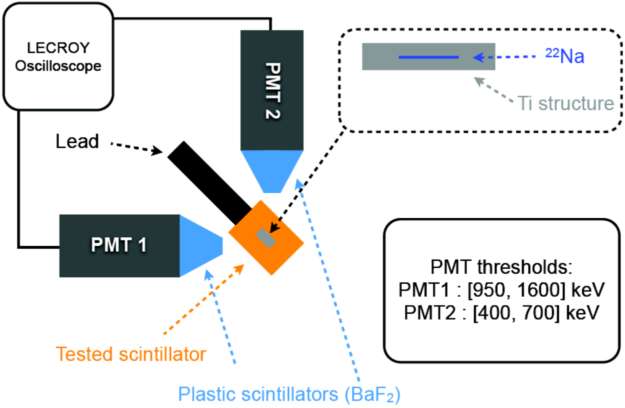
- **Positron identification :**
  $\rightarrow$ 2 contributions in prompt signal :
  o-Ps state observation via detection of 2γs of 511keV each after the ionization signal



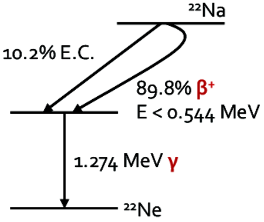
Positron Annihilation Lifetime spectroscopy (PALS)

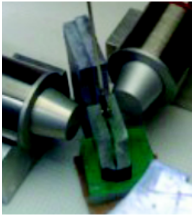
- Dedicated setup to study o-Ps properties in common liquid scintillators

«*Characterization of positronium properties in doped liquid scintillators*» (Phys. Rev. C - 2013 - NuToPs ANR)



Source: ^{22}Na





Fit model (RooFit)

- 3-exponential + constant convoluted with a gaussian to model detector resolution ($\sigma_{\text{det}} \sim 120$ps) : $F(t) * G(0, \sigma_{\text{det}})$ with :

$$F(t) = \sum_{i=1}^{3} A_i e^{-t/\tau_i} + C$$

- A=effective amplitude, τ=lifetime
- $i = 1, 2$: direct annihilation and p-Ps decay
- $i = 3$: o-Ps decay
- C : accidental background

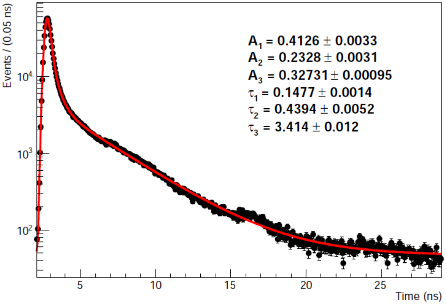
o-Ps formation probability

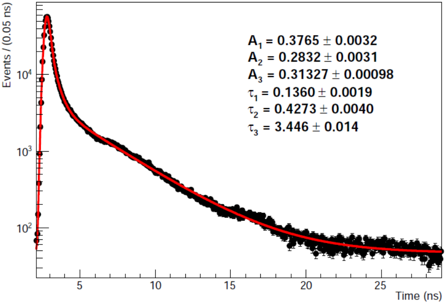
$$f = \frac{A_3 \tau_3^{\text{void}}}{(A_A + A_3 + A_K)\tau_3^{\text{void}} + (A_A - A_K)(\frac{\epsilon_3}{\epsilon_2} - 1)\tau_3}$$

- A_A and A_K : numbers of annihilations observed and predicted in the source support
- ϵ_2 and ϵ_3 respectively the 2 and 3 gamma decays detection efficiencies
- τ_3^{void}=o-Ps lifetime in vacuum (142ns)

Positron Annihilation Lifetime spectroscopy (PALS)

- Target and Gamma Catcher (GC) liquid scintillators have been tested



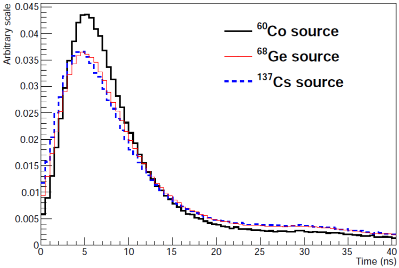


Scintillator	o-Ps formation fraction	o-Ps lifetime
Target	47.6 ± 1.3 %	3.42 ± 0.03 ns
Gamma Catcher	45.6 ± 1.3 %	3.45 ± 0.03 ns

→ Lifetime similar but formation fraction slightly different

→ Same result found by comparing various kind of liquid scintillators (LAB, PC)

Pulse shape references and fit procedure



- Pulse shape depends on energy
- 2 sources used as reference : ^{137}Cs ($\sim$ 660KeV) and ^{60}Co ($\sim$ 2.5MeV)

- Fit procedure (on the prompt signal) :
  - fit function using 2 distributions based on ^{137}Cs reference PS, shifted by Δt
  - idem with 2 distributions based on ^{60}Co reference PS
  - Normalization of the two peaks is free in a range of 60% around the expected one (2 γs of 511keV expected)
  - parameters obtained : Δt and amplitudes of ionization and annihilation signals, for each case
- For tagging algorithm, final result is given by the mean values obtained using the ^{137}Cs and the ^{60}Co reference source, to take into account the energy dependence

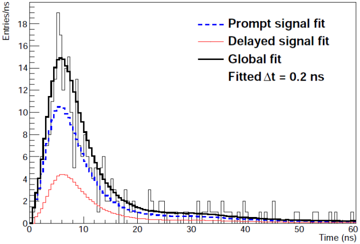
χ^2 analysis

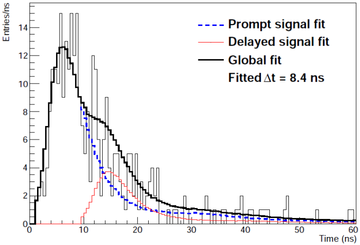
$$\chi^2 = 2\sum_{i=1}^{N}\left[\nu_i - n_i + n_i ln(\frac{n_i}{\nu_i})\right] + \sum_{j=1}^{2}\frac{N_j^2}{\sigma_{N_j}^2}$$

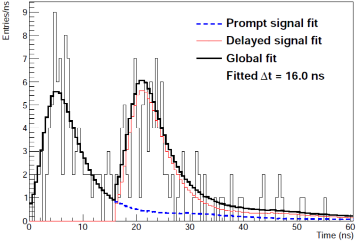
- n stands for the data
- ν is the expected value
- N_j is the normalization shift ($\pm 60\%$)
- σ_{N_j}=0.2, error for each reference PS

- $\sim$ 400 pulses per event distributed on 300 bins
  $\rightarrow$ Poisson statistics (first term)
- $\chi^2 < 2$ cut to select well fitted events

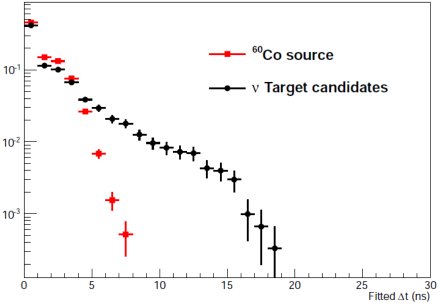
Pulse shape analysis in DC







Results - statistical effect



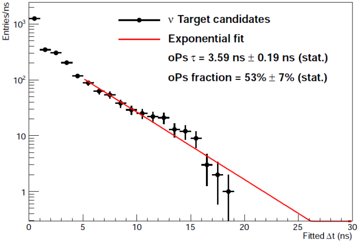
- Comparison between neutrino candidates («DCII» IBD sample - 8249 events) and cobalt results (no o-Ps)

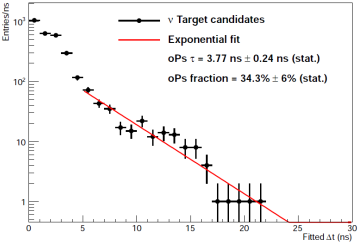
  «Reactor electron antineutrino disappearance in the Double Chooz experiment»

  (Phys. Rev. D - 2012 - DC collaboration)

- Energy cuts applied : $[1.2\text{MeV}, 3\text{MeV}]$
  - under 1.2 MeV : first peak too small
  - over 3 MeV : second peak masked by the fist peak tail
- Cobalt distribution still "large"
- But effect clearly visible for $\Delta t > 5\text{ns}$

Results - Single event basis





- Only statistical errors reported on plots
- Different shapes are obtained depending on reference used
- Exponential fit with cut at 5 ns (see previous slide)
- o-Ps fraction energy dependency included in systematic errors

	o-Ps formation fraction error [%]	o-Ps lifetime error [ns]
Measurements with dedicated setup	47.6 ± 1.3	3.42 ± 0.03
DC (II publication) results	44 ± 5 (stat.) ± 12 (sys.)	3.68 ± 0.15 (stat.) ± 0.17 (sys.)

Source of error	o-Ps formation fraction error [%]	o-Ps lifetime error [ns]
Source element	9	0.09
Cut on the vertex distance	1.25	0.019
Source position	5	0.055
Fit interval	7	0.14
Total systematics	12	0.17
Statistics	5	0.15

Conclusion and Perspectives

- Lifetime and formation fraction measured in DC detector in good agreement with dedicated setup measurements
- o-Ps formation could be exploited in $\bar{\nu}$ detectors for additional background detection
- Quite challenging due to the short lifetime of $\sim$ 3ns
- Used on a statistical basis for e^+/e^- discrimination in Borexino
- **Double Chooz $\rightarrow$ first demonstration of the possibility to tag such a process on single event basis using a pulse shape analysis**
- Due to energy dependence $\rightarrow$ can not be used directly for background reduction, but possibility to assign a probability to each event of being an o-Ps decay for dedicated studies on pure samples
- Excellent starting point for future projects using liquid scintillators for $\bar{\nu}$ detection (DC detector not designed for this kind of analysis)