Observation of ortho-Positronium formation in Double Chooz

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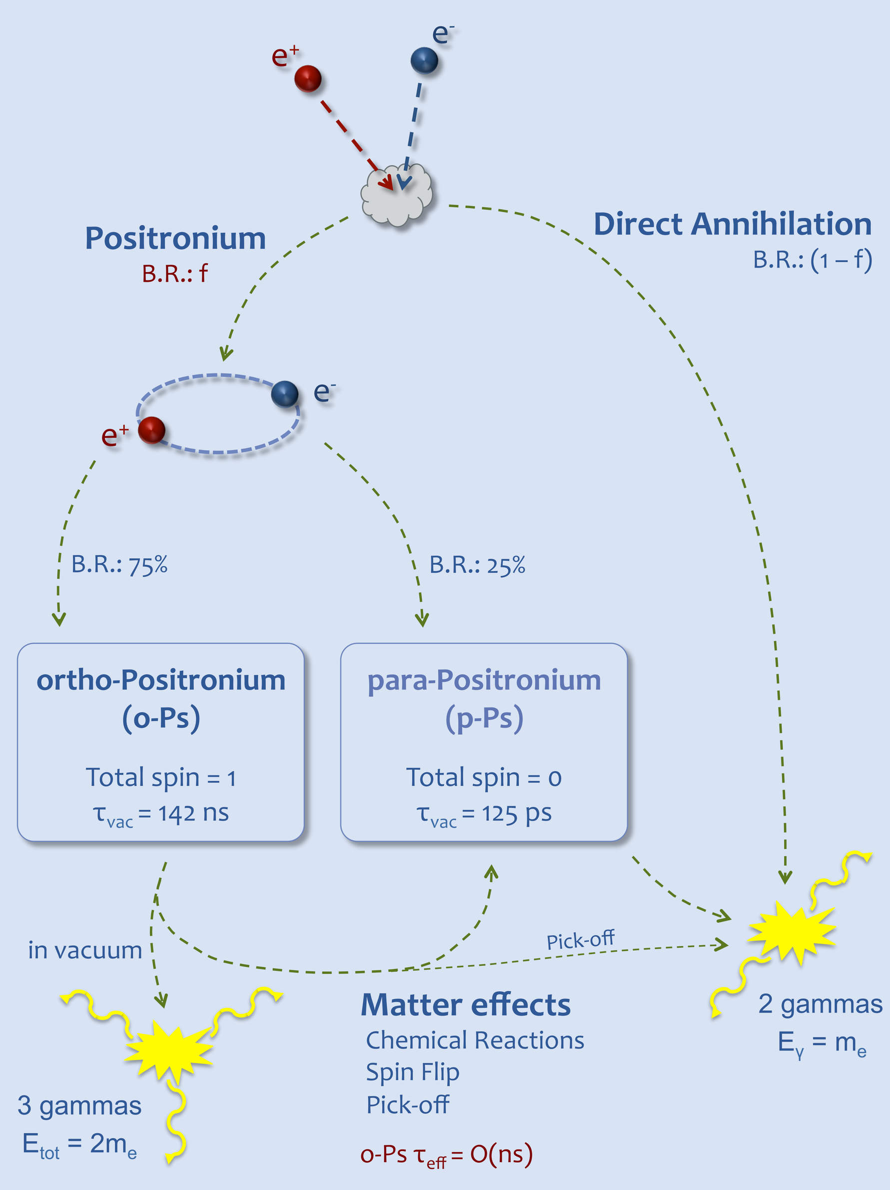
1. Positronium Physics



Electron – positron interaction can resolve into either direct annihilation or the formation of a metastable bound state, called Positronium (Ps) [1]. *Its formation probability (f) depends on the material the Ps forms in.*

The Ps ground state has two possible configurations: **para-Positronium (p-Ps**, B.R.: 25%), with total spin 0, and **ortho-Positronium (o-Ps**, B.R.: 75%), with total spin 1. Both configurations are unstable, due to the possibility of e^+ - e^- annihilation: *in vacuum*, p-Ps has a lifetime of 125 ps, while o-Ps lives three orders of magnitude longer (142 ns). For C conservation, p-Ps decays into two (511 keV) gammas, while o-Ps decays into 3 gammas, of $2m_e$ total energy. Decays into a higher number of photons have a BR = $O(10^{-6})$.

Ps interactions with matter could lead to o-Ps conversion into p-Ps, pick-off being the leading effect in Liquid Scintillators. Matter effects result into a *considerable shortening of the o-Ps mean life to a value depending on the material* (a few ns). The decay into three gammas is usually reduced to a negligible fraction.

For particle identification purposes, only o-Ps is relevant, as the typical fast scintillation time is of the order of a few ns (see Box 2).

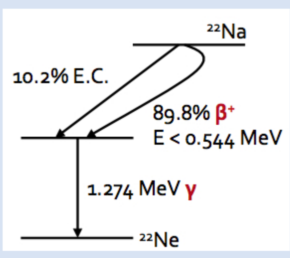
O-Ps properties in the scintillator of Double Chooz

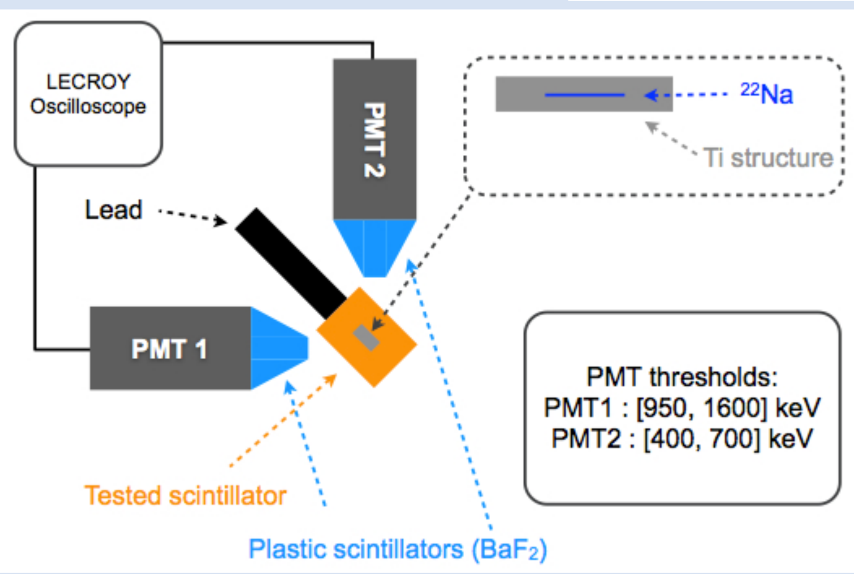
O-Ps formation probability and effective lifetime have been measured in the most common liquid scintillators and doped liquid scintillators with a dedicated setup [2,3]. This PALS setup (right picture) uses a ^{22}Na positron source inserted in the scintillator sample.

The effective lifetime is measured to be around 3 ns, with a weak dependence on the scintillator and no dependence on the dopant concentration. On the other hand, the formation probability shows significant variations depending mostly on the dopant concentration.

*The **Double Chooz** liquid scintillator is a mixture of dodecane, PXE, PPO and bis-MSB, doped with 1 g/l Gd. In it,* ***o-Ps has a formation probability of (47.6 ± 1.3)% and an effective mean life of (3.42 ± 0.03) ns.***

^{22}Na source emits a positron (BR: ~0.9, Emax = 544 keV), followed by a 1.274 MeV gamma. The setup measures the time interval between this gamma and the positron annihilation to extract the o-Ps properties in the tested scintillator.





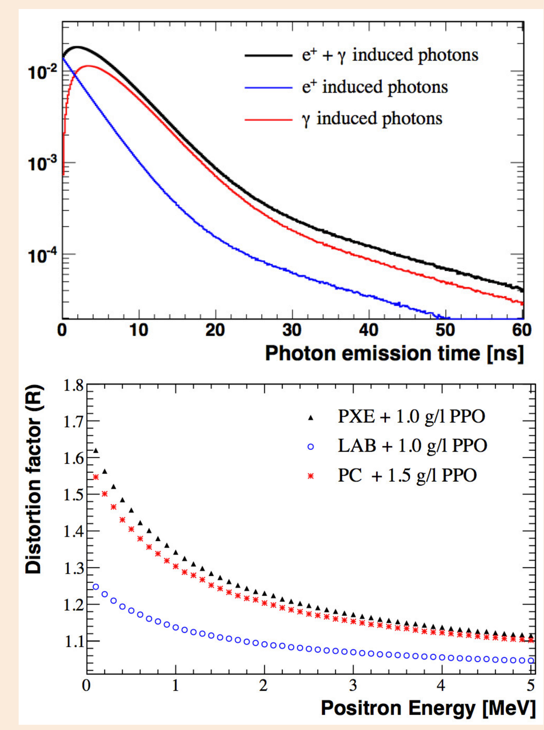
Top: Scheme of the 22Na source. **Bottom:** Cartoon of the PALS setup used for characterizing o-Ps in the different scintillators.

2. O-Ps in e^+ - e^- discrimination

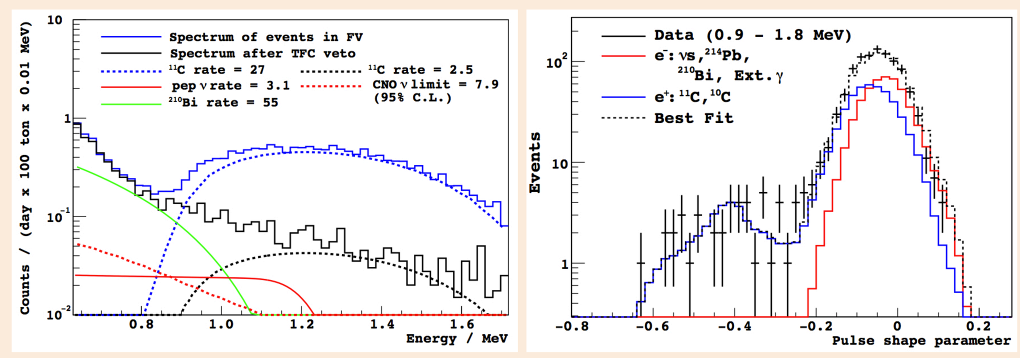
Ps can play an important role in particle identification for what concerns the e^+ - e^- separation. Electrons and positrons have the same energy loss and, hence, provoke identical scintillation pulses. However, the formation of Ps introduces a delay (equal on average to the Ps lifetime) which separates the light pulse from the one from the annihilation gammas, deforming the global positron pulse shape (plots on the right). In case the delay is wide enough, the two contributions can be resolved (see next boxes).

As the scintillation fast time is typically around a few nanoseconds (2.6 ns in Double Chooz [4]), the only Ps configuration capable of producing a pulse shape distortion is the o-Ps.

Pulse Shape Discrimination (PSD) is a well-established technique for particle identification in liquid scintillator detectors. It exploits the difference in the pulse shapes caused by particles with different energy loss and then it is effective for heavy-light particles discrimination, but fails in the electron–positron separation. Exploiting the o-Ps formation can allow to recover the PSD efficiency.



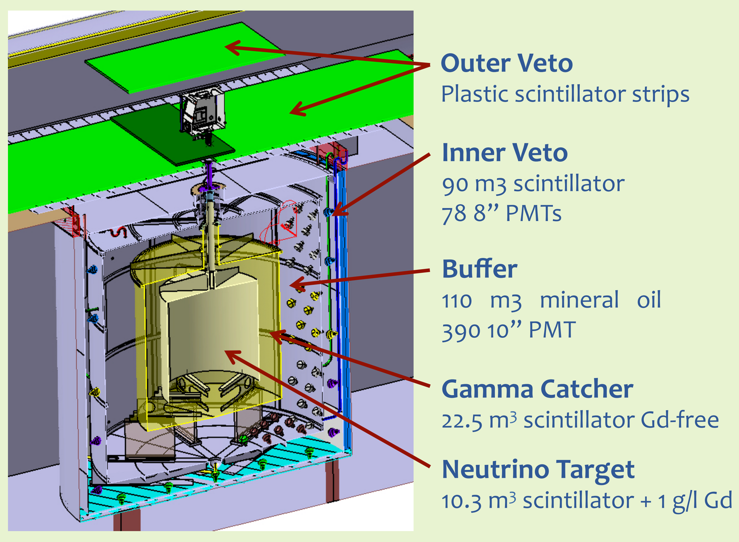
Top: positron pulse shape resolved into its components (positron energy loss and annihilation gammas) after o-Ps formation. **Bottom:** Dependence of the pulse deformation on the positron energy.



Left: global Borexino spectrum in the region of the *pep* spectrum shoulder. **Right:** distribution of the electron-positron discrimination parameter obtained exploiting the o-Ps formation.

The o-Ps–enhanced PSD has been already successfully applied for the observation of the solar *pep* neutrinos in Borexino [5]. The use of an e^--e^+ discrimination parameter exploiting the o-Ps formation has been the key factor for separating the signal (e^-) from the background (e^+ from ^{11}C).

3. The Double Chooz Experiment



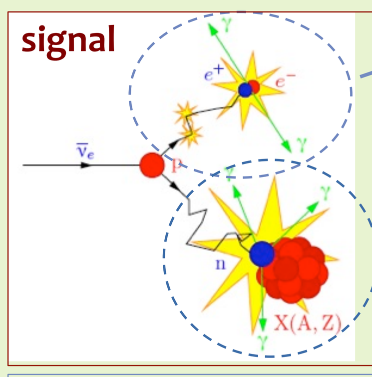
Double Chooz [6] detects the oscillated flux of anti-neutrinos at 1 km from the nuclear reactors to measure the θ_{13}.

The anti-neutrino detection is done via inverse beta decay (IBD), i.e. via the delayed coincidence of a **positron** and a neutron absorption.

Most of the background sources, both correlated and not, mimic the IBD coincidence with a prompt signal given by an **electron**. Therefore, an electron-positron discrimination could bring a further background rejection.

In Double Chooz, we observed the formation of ortho-Positronium in the neutrino candidates sample (next boxes).

signal



→ prompt signal
positron + annihilation gammas

→ delayed signal
n absorption on Gd

background

Accidentals:

radioactivity (incl. **electrons**) + cosmogenic *n*

Correlated:

^{9}Li & ^{8}He:	**electron** + *n*
Stopping muons:	**Michel electron** + *n*
Fast n:	recoiling proton + *n*

4. O-Ps Analysis

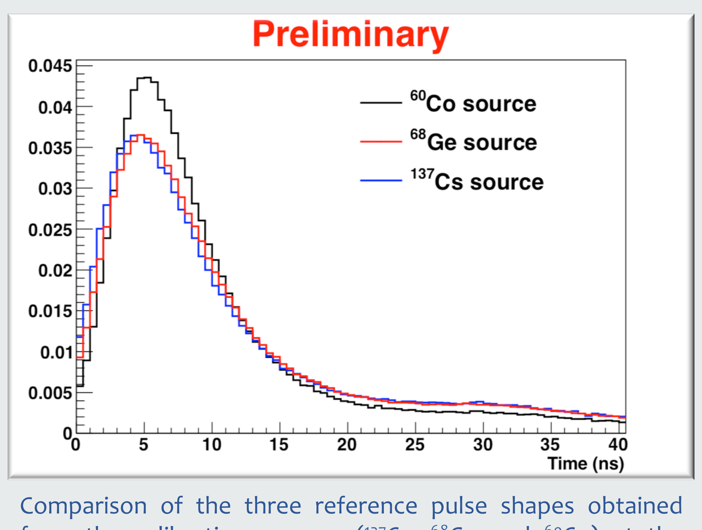
Several events in the neutrino candidate data set (with *n* capture on Gd) show a double pulse in the prompt event. This leads to hypothesize the formation of o-Ps: the first peak is given by ionization and the second by the delayed annihilation. To corroborate this hypothesis, we developed an algorithm based on the recognition of the two pulses to extract the delay distribution (next box).

Anti-ν data sample with *n* absorption on Gd + cuts on:
χ^2 (< 2; see next box)
Prompt energy (in range [1.2, 3] MeV)

The algorithm fits each event prompt signal with two reference pulse shapes to extract the delay between them.

(Neutrino event and reference) pulse shapes are constructed correcting the hits time distribution for each PMT transit time (measured in laser runs) and for the photon time of flight.

The reference pulse shape are constructed from calibration data using the sources ^{137}Cs (662 keV), ^{68}Ge (1 MeV) and ^{60}Co (2.5 MeV) at the center of the Target. A spacial cut of 20 cm around the source is applied. The comparison among them shows a pulse shape dependence on energy (plot on the right).

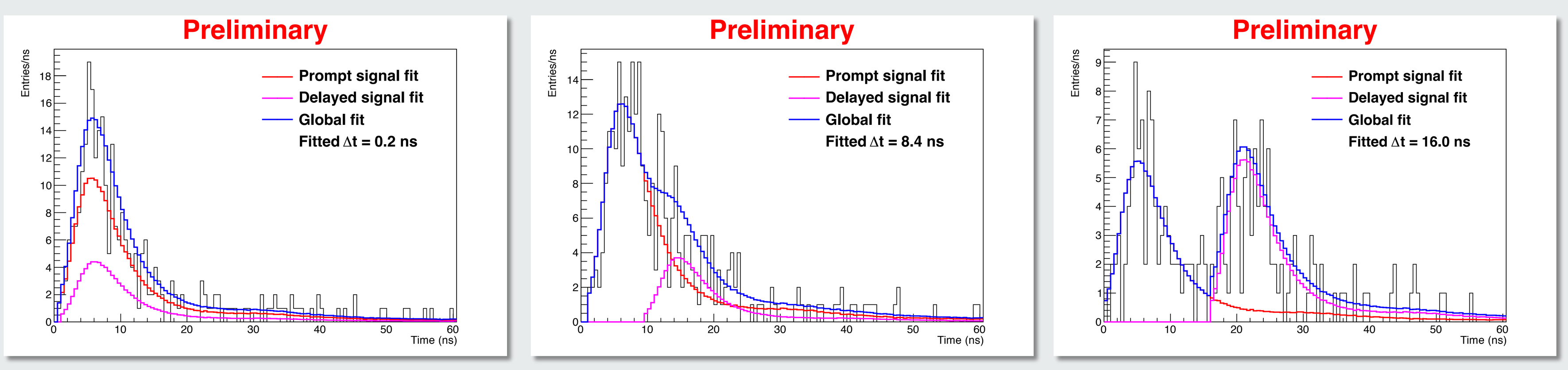


Comparison of the three reference pulse shapes obtained from the calibration sources (^{137}Cs, ^{68}Ge and ^{60}Co) at the detector center.

Fit of the prompt event pulse profile

For each neutrino event, the prompt pulse profile is fitted with the sum of two reference pulse shapes. The delay (Δt) separating them being a free parameter, as much as the first pulse shape starting point is free to vary in [-10, 0] ns to correctly match the first peak.

The amplitude of the two pulses is constrained by energetic criteria: the second pulse energy must be 1.022 MeV, while the first one has to account for the rest of the energy. The normalization is left free to vary of 60% around these values to account for energy non-linearities.



Examples of prompt event pulse fit with Δt = 0.2 ns (left), 8.4 ns (center) and 15 ns (right).

5. Results

Events whose fit has a $\chi^2 > 2$ are rejected.

The Δt spectrum obtained from the neutrino candidate sample is compared to the one obtained with the ^{60}Co source, where no o-Ps is expected. The distribution of the neutrino candidate sample clearly shows an excess of events at larger Δt, enforcing the hypothesis of o-Ps.

The o-Ps properties have been measured fitting the neutrino Δt distribution to an exponential. The distribution is fitted above 5 ns to exclude the region populated by the smearing observed in the ^{60}Co sample.

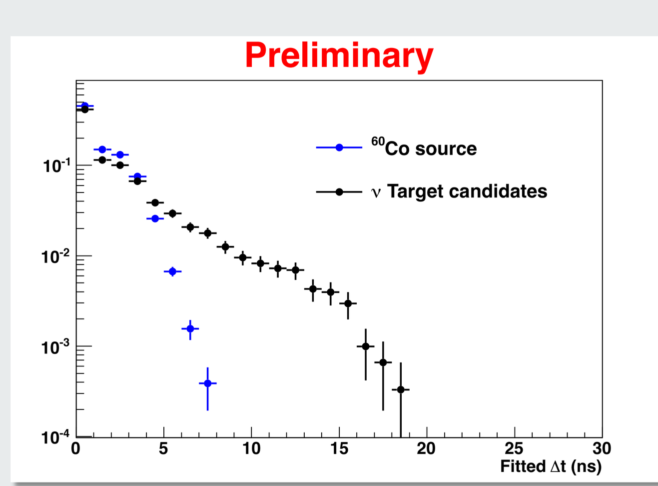
The fit result is sensitive to the choice of the reference pulse shape among the three available (box 4). The contribution to the systematic error accounting for this is evaluated as the semi-difference between the results at low (^{137}Cs) and high (^{60}Co) energy. Other contributions to the systematics come from variations in the method of building the reference curves and from variations of the fit interval.

The results from the fit, reported in the table below, are in excellent agreement with the measurements from the dedicated setup NuToPs.

Chi-square definition

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

ν_i: # of entries in the *i*-th bin of the reference PS
n_i: # of entries in the *i*-th bin of the event PS
N_j: normalization shift (± 0.6)
σ_{Nj} (= 0.2): uncertainty on N_j



Comparison of the Δt distributions obtained with the ^{60}Co source (blue), where no o-Ps is expected, and with the neutrino candidates data set (black).

Measured in:	o-Ps fraction	o-Ps lifetime [ns]
Double Chooz (PS: ^{60}Co and ^{137}Cs)	$42 \pm 5_{stat} \pm 12_{sys}$	$3.68 \pm 0.15_{stat} \pm 0.17_{sys}$
Dedicated setup (Box 1)	47.6 ± 1.3	3.42 ± 0.03

Conclusions

Although the Double Chooz detector was not conceived for such a measurement, it has been possible not only to observe the o-Ps formation on an event by event basis, but also to measure its formation probability and lifetime. This result suggests the possibility of assigning to each event the probability of being an o-Ps decay.

References

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