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Observation of ortho-positronium formation in Double Chooz

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Abstract

The aim of the Double Chooz experiment is to measure the neutrino mixing angle θ_{13} by detecting the reactor electron anti-neutrino via inverse beta decay. The positron-neutron delayed coincidence yields a sizeable background suppression; a further contribution might come from the development of techniques for an efficient identification of positrons. Pulse shape discrimination, a well-established technique for background rejection in liquid scintillator detectors, fails in separating positrons from electrons, as they give rise to identical light pulses. However, in some cases the positron decay is delayed by the formation of a positron-electron metastable bound state, called ortho-positronium (o-Ps), which introduces a delay between the light signal from the positron energy deposition in the scintillator and the one from the annihilation gammas. The consequent deformation in the positron-induced light pulse can be exploited to identify positrons with the pulse shape discrimination, as already successfully done statistically in Borexino.

In Double Chooz, we performed the first o-Ps formation tagging on an event-by-event basis. We also measured the o-Ps formation probability and its lifetime, finding $(44 \pm 13)\%$ and (3.68 ± 0.23) ns respectively. These values are in good agreement with independent measurements obtained with a dedicated setup.

Keywords: Pulse shape discrimination, Ortho-positronium, Double Chooz

1. Introduction

Electron-positron interaction can resolve into either direct annihilation or the formation of a metastable bound state, called Positronium (Ps) [1]. Its formation probability 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). However, matter effects result into a considerable shortening of the o-Ps mean life to a value depending on the material (a few ns).

Pulse Shape Discrimination (PSD) is a well-established technique for particle identification in liq-uid 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. Ortho-positronium can play an important role in particle identification for what concerns the e^+/e^- separation. The formation of o-Ps introduces a delay which separates the light pulse from the positron and the one from the annihilation gammas. In case the delay is wide enough, the two contributions can be resolved, allowing to recover the PSD efficiency.

The o-Ps enhanced PSD has been already successfully applied statistically for the observation of the solar pep neutrinos in Borexino [2]. 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).

Double Chooz [3] detects the oscillated flux of anti-neutrinos at 1 km from the nuclear reactors to measure the θ_{13} mixing angle. The anti-neutrino detection is done via inverse beta decay (IBD), i.e. via the delayed

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coincidence of a positron and a neutron absorption. The most important source of background in Double Chooz is given by cosmogenic βn-emitting isotopes. Therefore, an electron-positron discrimination could bring a further background rejection. In Double Chooz, we observed the formation of ortho-Positronium on an event-by-event basys (Sec. 3, 4).

2. Ortho-positronium properties in the Double Chooz scintillator

Formation probability and effective lifetime of o-Ps have been measured in the most common liquid scintillators and doped liquid scintillators with a dedicated setup [4, 5]. This PALS setup (figure 1) uses a ^{22}Na positron source inserted in the scintillator sample. ^{22}Na emits a positron (BR: ~ 0.9, $E_{max} = 544$ 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.

The Double Chooz liquid scintillator is a mixture of dodecane, PXE, PPO and bis-MSB, doped with 1 g/l Gd [6]. For this compound, we measured a o-Ps formation probability of $(47.6 \pm 1.3)\%$ and an effective mean life of (3.42 ± 0.03) ns.
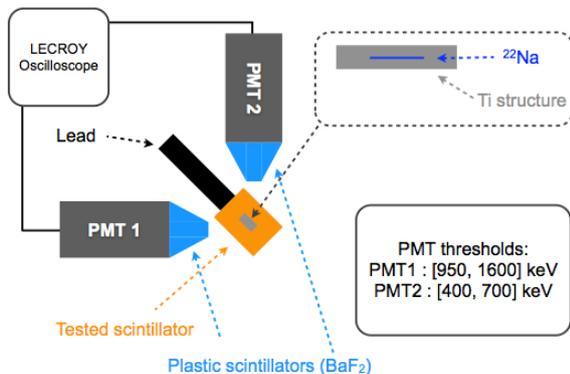

Figure 1: Cartoon of the PALS setup used for characterizing o-Ps in the different scintillators.

3. Ortho-positronium tagging algorithm

A detailed description of the analysis can be found in Ref. [7]. To observe the formation of o-Ps in Double Chooz, we developed an algorithm based on the identification of a double peak structure in the positron pulse shape. The first peak is given by the ionization and the

second by the annihilation. The algorithm fits each signal with two reference pulse shapes to extract the time delay between them.

Positron and reference pulse shapes are constructed correcting the hits time distribution for each PMT transit time and for the time of flight from the event reconstructed vertex. The reference pulse shape are constructed from calibration data using the sources ^{137}Cs, ^{68}Ge and ^{60}Co at the center of the target. The comparison among them shows a pulse shape dependence on energy (figure 2).

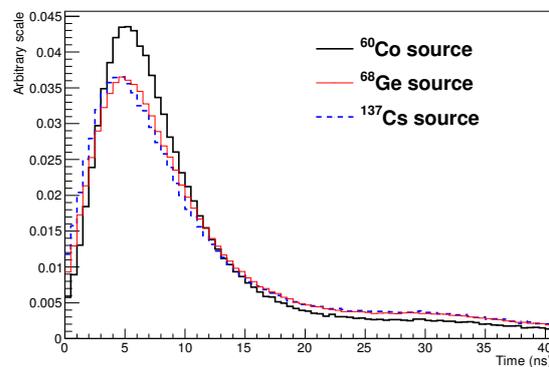Figure 2: Comparison of the three reference pulse shapes obtained from the calibration sources (^{137}Cs, ^{68}Ge and ^{60}Co) at the detector center.

For each positron event, the 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 $\pm 60\%$ around these values to account for energy non-linearities. Few examples of fit are given in figure 3.

4. Results on the ortho-positronium properties

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 (selection cut of Ref. [3] with energy in the range $[1.2, 3]$ MeV) clearly shows an excess of events at larger Δt, enforcing the hypothesis of o-Ps (figure 4).

The o-Ps properties have been measured fitting the Δt distribution with an exponential. The distribution is
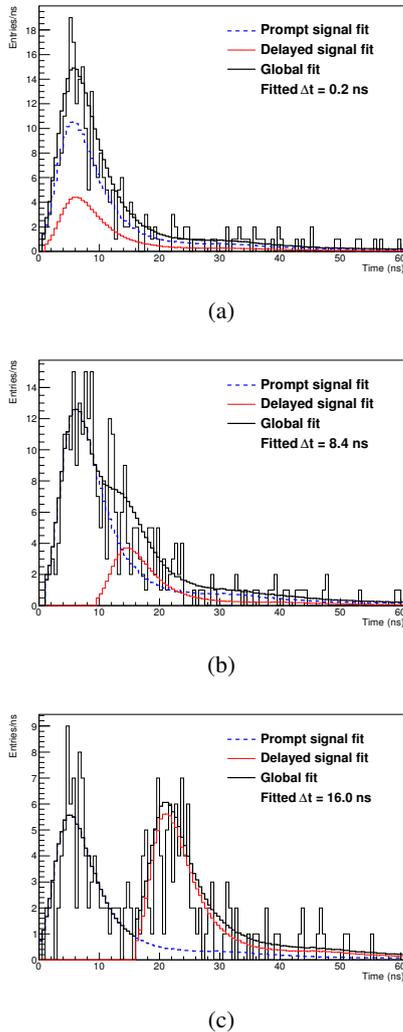
(a)

(b)

(c)

Figure 3: Three examples of o-Ps fit. The dashed blue line represents the fit of the first time profile, the thin red line the fit of the second one and the thick black line is the total fit.

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 (figure 2). 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 table 1, are in agreement with the measurements from the dedicated setup.
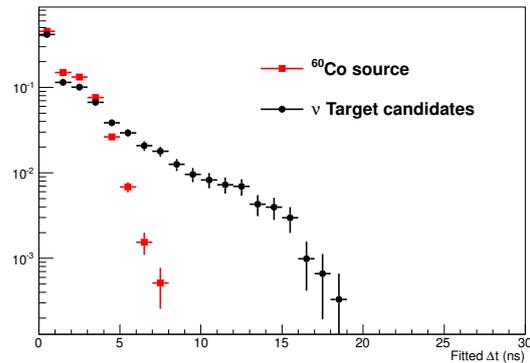

Figure 4: Distribution of the Δt value determined by the fit for the ^{60}Co sample (red squares), and for the neutrino sample (black dots).

	o-Ps fraction	o-Ps lifetime [ns]
Double Chooz	$42 \pm 5_{stat} \pm 12_{sys}$	$3.68 \pm 0.15_{stat} \pm 0.17_{sys}$
PALS (Sec. 2)	47.6 ± 1.3	3.42 ± 0.03

Table 1: Comparison of the oPs fraction and lifetime measured with the present analysis and the dedicated setup.

5. 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 is also an excellent starting point for future projects aiming at the liquid scintillation technology for anti-neutrino detection.

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