1. Positronium Physics

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

The Ps ground state has two possible configurations: para-Positronium (Ps-p, B=I/2), with total spin 0, and ortho-Positronium (Ps-o, B=1/2), with total spin 1. Both configurations are unstable, due to the possibility of a Ps-annihilation in vacuum; Ps-p has a lifetime of 155 ps, while Ps-o lives three orders of magnitude longer (424 ns). For C conservation, Ps-p decays into two (31 keV) gammas, while P-o decays into 3 gammas, of 2m, total energy. Decays into a higher number of photons have a BR = O(%)..

Ps interactions with matter could lead to Ps conversion into p-Ps, pick-off being the leading effect in Liquid Scintillators. Matter effects result in a considerable shortening of the Ps mean life to a value dependent 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).

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 positron and 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.

3. The Double Chooz Experiment

Several events in the neutrino candidate data set (with a capture on Gd) show a double pulse in the prompt event. This lead to the hypothesis 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).

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

(Neutron 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 90Co (662 keV), 137Cs (661 keV) and 208Tl (295 keV) at the center of the target. A special cut of 30 cm around the source is applied. The comparison among them shows a pulse shape dependence on energy (plot on the right).

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 [0,Δt] ns to correctly match the first peak.

The amplitude of the two pulses is constrained by energetic criterion: the second pulse energy must be 1.02 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.

4. O-Ps Analysis

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5. Results

Events whose fit has a χ² < 1 are rejected.

The 2σ spectrum obtained from the neutrino candidate sample is compared to the one obtained with the 60Co source, where no o-Ps is expected. The distribution of the neutrino candidate sample clearly moves 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 remaining observed in the 60Co 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 (2σ) and high (6σ) confidence level. 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.

6. Conclusion

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