Measurement of ortho-Positronium Properties in Liquid Scintillators

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1. Positronium Physics

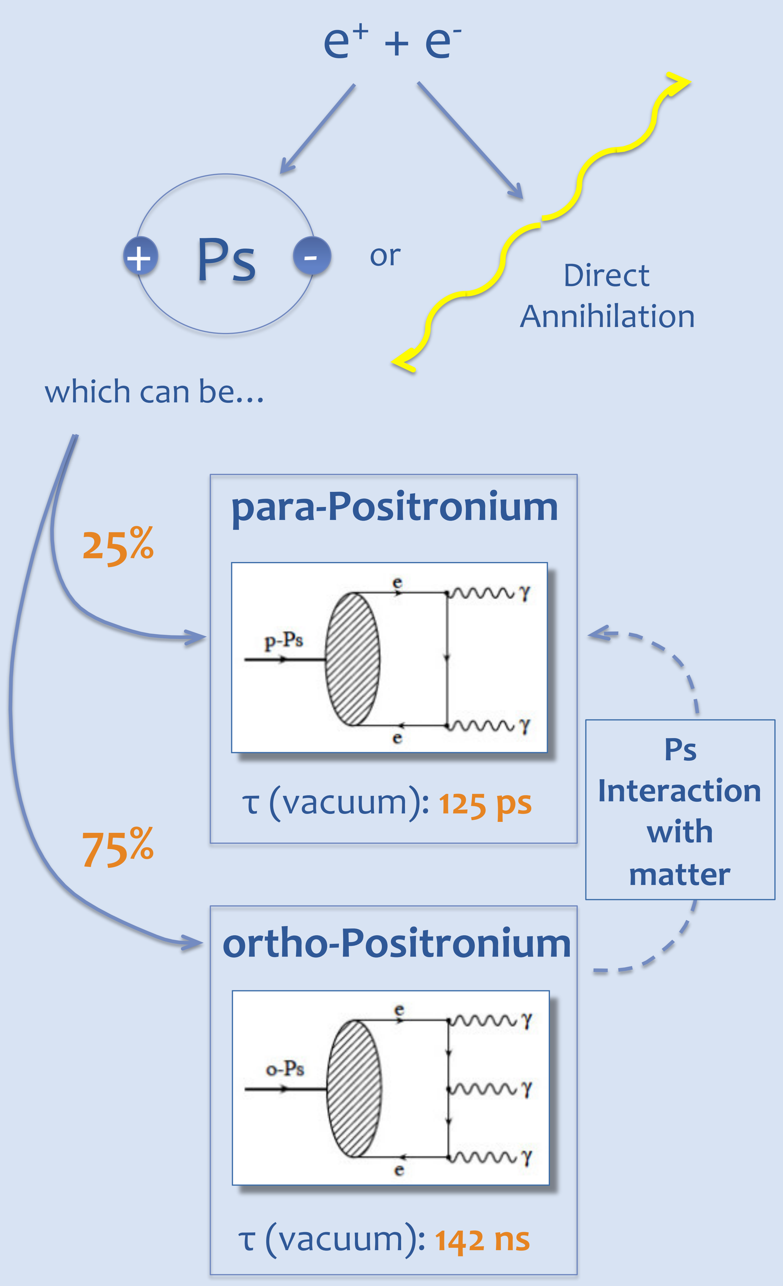
Positronium (Ps) is an e^+ - e^- bound state [1]. In the state S, the Ps total spin can be 0 (**para-Positronium**, p-Ps) or 1 (**ortho-Positronium**, o-Ps). Both states are unstable, due to the possibility of e^+ - e^- annihilation. If C is conserved, p-Ps (mean life: 125 ps) decays into two 511 keV gammas, while o-Ps (mean life: 142 ns) decays into 3 gammas of total energy equal to twice the electron mass (decays into a higher number of photons have a BR = $O(10^{-6})$).

Positrons in matter can undergo direct annihilation or form Positronium. **The probability of Ps formation, *f*, depends on the material the Ps forms in.**

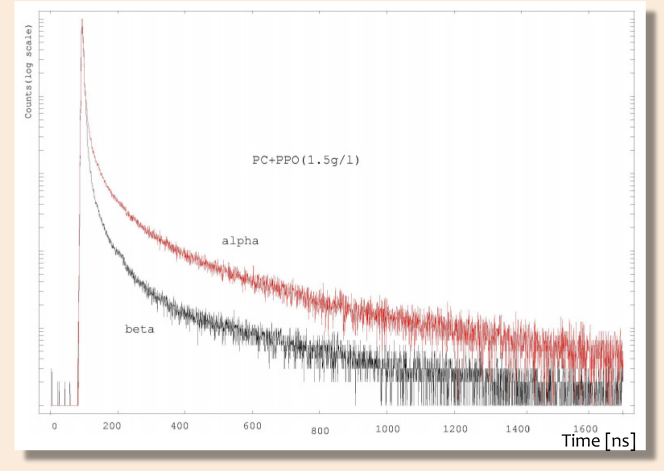
Para-Positronium and ortho-Positronium are produced in a ratio of 1:3. However, **Ps interaction with matter matter** could lead to o-Ps conversion to p-Ps. Such interactions include

- *Chemical reactions* (oxidation or compound formation)
- *Magnetic effects* (spin flip)
- *Pick-off* (positron annihilation with an anti-parallel spin electron of the medium)

Pick off is the leading effect in Liquid Scintillators. **o-Ps interaction with matter results into a considerable shortening of its mean life to a value depending on the material (a few ns)**. The decay into three gammas is usually reduced to a negligible fraction.



2. Pulse Shape Discrimination (PSD)



The light pulse from a scintillator is modeled as the superposition of three exponentials

$$P(t)=\sum_{i=1}^{3} A_i \exp(-t/\tau_i)$$

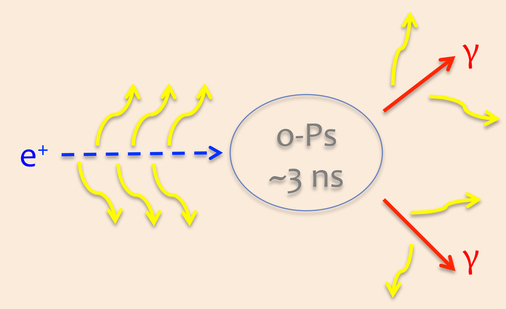
The light response depends on the crossing particle's dE/dx: the higher dE/dx, the larger the fraction of energy that goes into excitation to triplet states (characterized by a longer de-excitation time).

In the MeV range, heavy particles (protons, alphas, ions) lead to a larger triplet states excitation than light particles (electrons, positrons), due to a larger dE/dx.

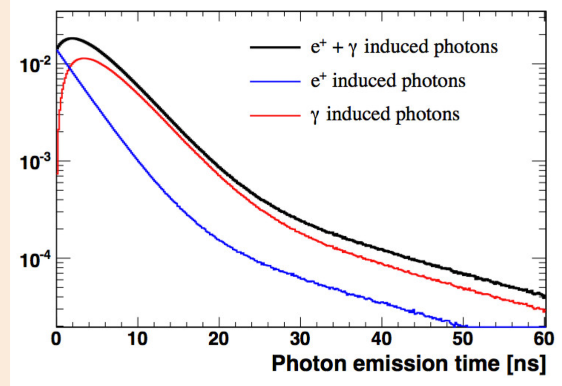
Scintillator	τ1 [ns]	τ2 [ns]	τ3 [ns]	A1 [%]	A2 [%]	A3 [%]
PC + 1.5 g/l PPO	3.57	17.61	59.9	89.5	6.3	4.2
PXE + 1.0 g/l PPO	3.16	7.7	34	84.0	12.0	2.9
LAB + 1.0 g/l PPO	7.46	22.3	115	75.9	21.0	3.1

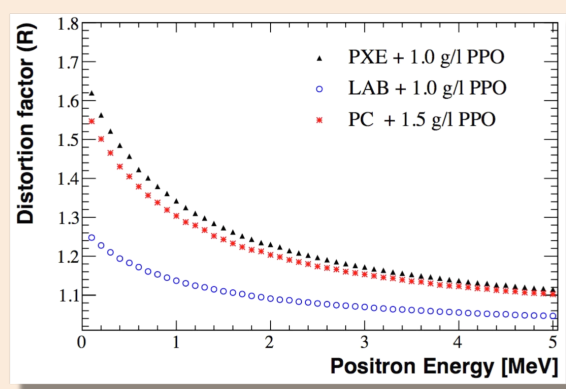
Therefore, PSD is very efficient in the discrimination of light particles from heavy particles. On the other hand, positrons of energy *E* induce the same light pulse of electrons of energy $E + 2m_e$. Therefore **PSD is inefficient for discriminating positrons from electrons.**

3. Exploiting o-Ps in PSD



In large volume LS detectors, the annihilation gammas cannot be disentangled from positrons, even after o-Ps, as the delay between them is of the same order of magnitude as scintillation light emission process. However, **o-Ps can induce a significant distortion in the pulse shape**, as the contribution from gammas is shifted of the o-Ps decay time. The distortion is energy dependent.





Applications

Anti-neutrino detection

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

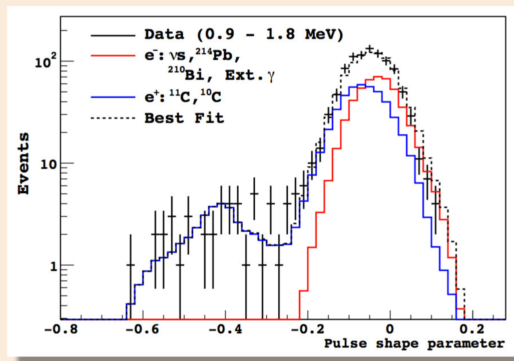
Enhancing the electron-positron discrimination can shrink the background due to

- Accidentals
- Correlated e^- - n (cosmogenic ^9Li and ^8He)

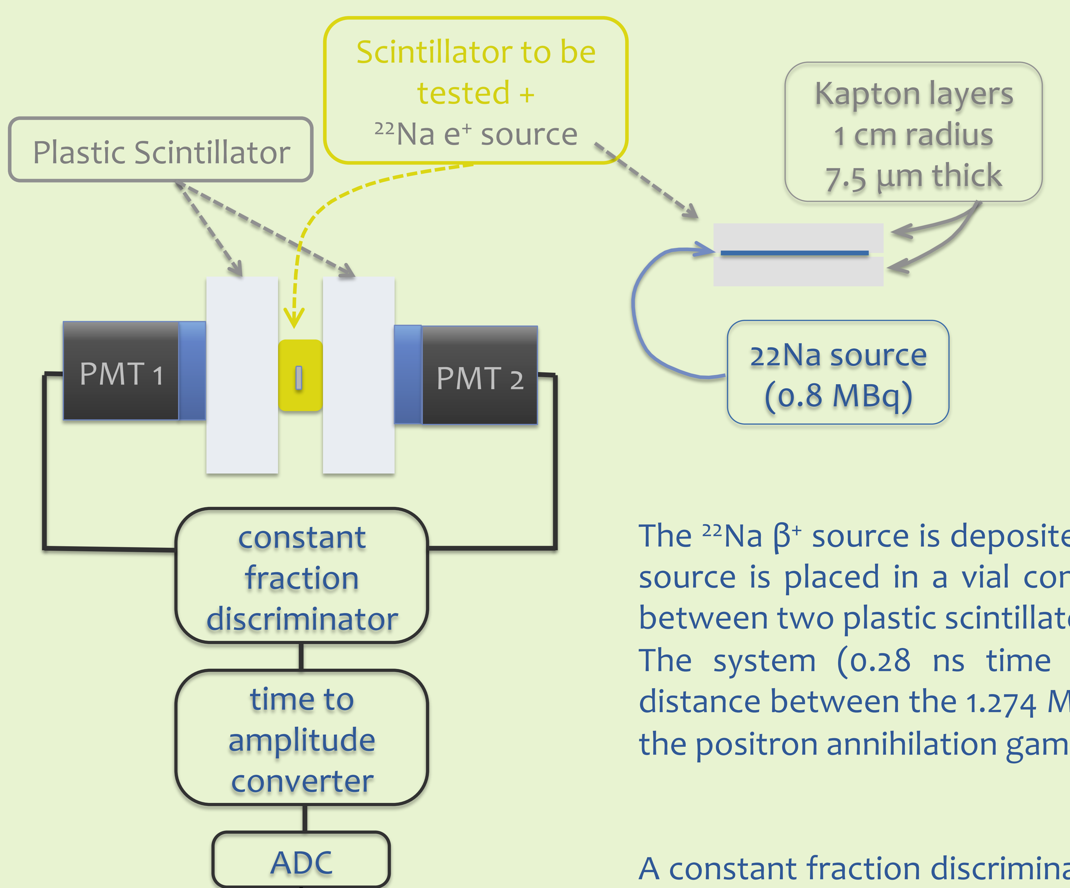
Cosmogenic Background Rejection

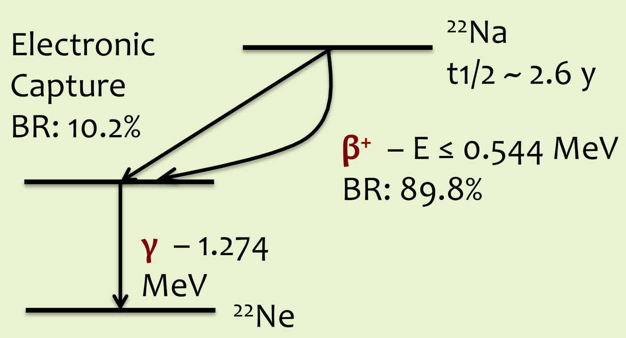
Several β^+ emitters are produced by cosmic muons, unavoidable contamination in underground low background experiments.

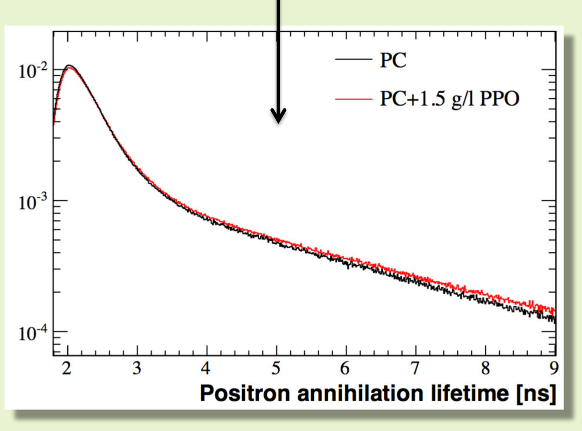
Technique successfully exploited in the solar *pep* ν rate measurement in Borexino [2]



4. Experimental Apparatus







The ^{22}Na β^+ source is deposited between two identical Kapton layers. The source is placed in a vial containing the scintillator to be characterized, between two plastic scintillator detectors.
The system (0.28 ns time resolution at FWHM) measures the time distance between the 1.274 MeV gamma (prompt signal: E > 900 keV) and the positron annihilation gammas (delayed signal: 350 keV < E < 500 keV).

A constant fraction discriminator generates a fast timing signal whenever a gamma of proper energy is detected. A time to amplitude converter produces a voltage linearly increasing with time, starting at the prompt signal detection and stopping at the delayed signal. The output is digitized by a 4096 channels ADC.

The system is calibrated using a ^{60}Co source. Each ADC channel corresponds to 10.6 ps. The resolution (0.28 ns FWHM) is measured with the fast coincidence (182 ps) gammas from ^{207}Bi.

5. Characterization of o-Ps in Liquid Scintillators [3]

Five LS have been tested: **PC, PXE, LAB, OIL, PC + 1.5 g/l PPO**. For each sample, 3 to 5 measures were taken with a ~1 x 10^6 statistics at room temperature.

The data are fitted with the function F(t), where

- A_1 and τ_1 are the effective amplitude and mean life of the direct annihilation and p-Ps, unresolvable components
- A_2 and τ_2 are the o-Ps amplitude and mean life
- C accounts for the accidental background
- X(t) is the step function

Fit Function

$$F(t)=\chi(t>t_0)\cdot\left(\sum_{k=1,2}\frac{A_k}{\tau_k}e^{-t/\tau_k}+C\right)$$

Resolution Function

$$G(t)=\sum_{i=1,2}\frac{g_i}{\sqrt{2\pi\sigma_i^2}}\cdot e^{-\frac{t^2}{2\sigma_i^2}}$$

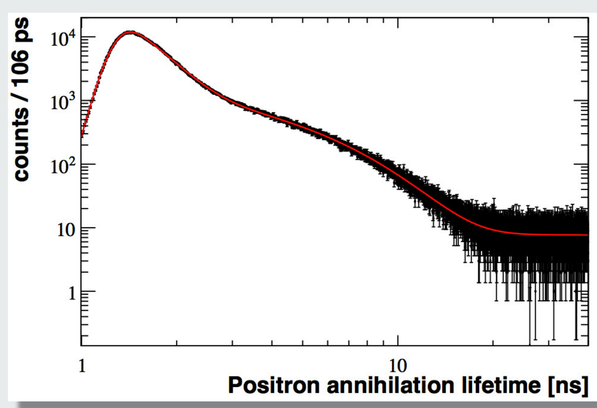
F(t) is convoluted with the resolution function, G(t), in which σ_1 = 110 ps and g_1 = 0.8, while σ_2 = 160 ps and g_2 = 0.2.

The o-Ps formation probability in the LS is computed as

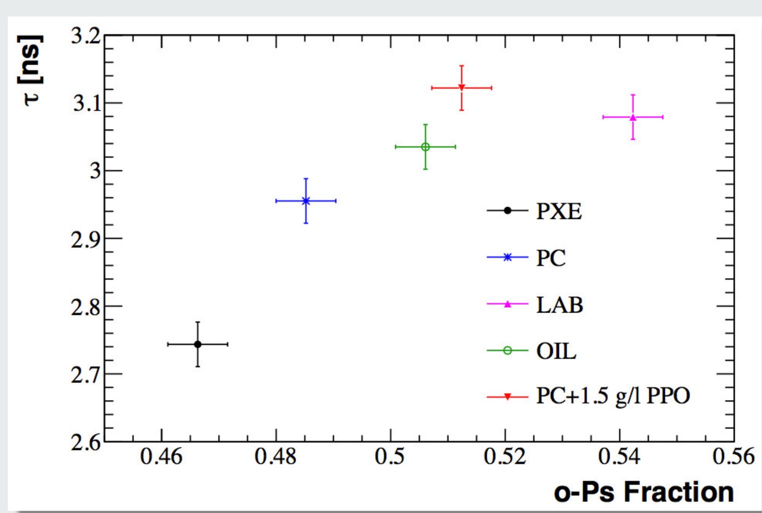
$$f=\frac{A_2}{A_1+A_2-A_k}$$

where A_k is the fraction of o-Ps annihilating in Kapton (0.206 ± 0.002).

The distribution of the deviation of the single measurement from the average of the corresponding sample is fit with a gaussian, whose σ is taken as systematic error. The resulting systematics are 0.5% and 0.03 ns.



Fitted o-Ps time spectrum. All the fits give a normalized X^2 in the range [0.85 – 0.98] .



Scintillator	f2	τ [ns]
PC	0.485 ± 0.005	2.96 ± 0.03
PXE	0.466 ± 0.005	2.74 ± 0.03
LAB	0.542 ± 0.005	3.08 ± 0.03
OIL	0.506 ± 0.005	3.04 ± 0.03
PC + 1.5 g/l PPO	0.512 ± 0.005	3.12 ± 0.03

o-Ps mean life τ and formation probability *f* in the tested liquid scintillators.

6. Characterization of o-Ps in Doped Liquid Scintillators [4]

o-Ps properties have been studied in **Gd and Nd loaded LAB samples**, i.e. in the LS used in the reactor experiments [5-7] and SNO+ [8]. Several concentrations have been tested, at room temperature. For each of them, 3 to 5 measures were taken with a ~1x10^6 statistics.

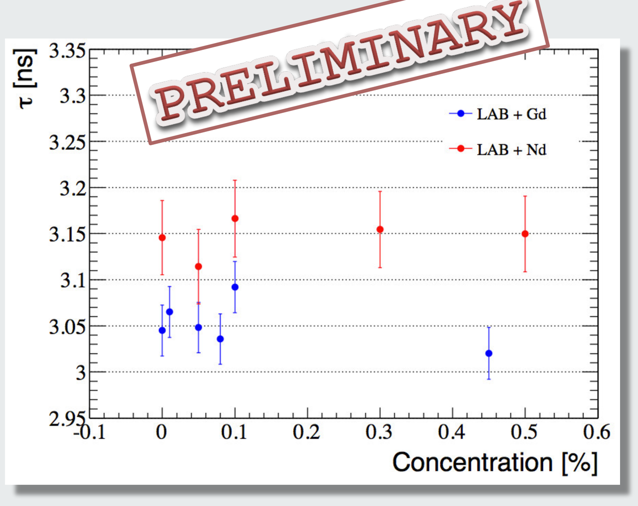
This set of data has been fitted with the superposition of three exponentials and a constant, the first two exponentials accounting for the direct annihilation and p-Ps, the third exponential for the o-Ps and the constant for accidental background. The fitting function is convoluted with a gaussian with σ = 120 ps.

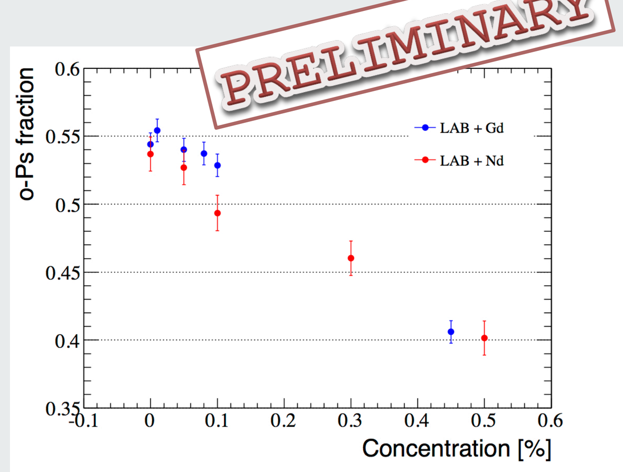
The o-Ps two gamma decay lifetime (τ) can be extracted from the third exponential time constant taking into account the o-Ps lifetime in vacuum (142 ns).
The o-Ps formation probability f is computed on the basis of the three exponential time constants and amplitudes, the fraction of annihilations in Kapton and the detection efficiencies of the two (ε_2) and three (ε_3) gamma decays.

Since ε_2 and ε_3 could not be precisely measured, the semi-difference between *f* computed in the two extreme cases (ε_3 = 0 and $\varepsilon_3 = \varepsilon_2$) is taken as systematic error, while the central value is taken as measure of *f*. The systematic contribution computed in Box 5 is also taken into account (1.3%).

Nd concentration	f	τ [ns]
No Nd	0.537 ± 0.013	3.15 ± 0.04
0.05%	0.527 ± 0.013	3.11 ± 0.04
0.1%	0.494 ± 0.013	3.17 ± 0.04
0.3%	0.460 ± 0.013	3.15 ± 0.04
0.5%	0.402 ± 0.013	3.15 ± 0.04

Gd concentration	f	τ [ns]
No Gd	0.544 ± 0.008	3.05 ± 0.03
0.01%	0.554 ± 0.008	3.07 ± 0.03
0.05%	0.540 ± 0.008	3.05 ± 0.03
0.08%	0.537 ± 0.008	3.04 ± 0.03
0.1%	0.529 ± 0.008	3.09 ± 0.03
0.45%	0.406 ± 0.008	3.02 ± 0.03





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