Developing a phantom for the positronium imaging evaluation

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Abstract

In this contribution a new phantom for PET measurements is described. The proposed phantom (much like NEMA IEC) will consist of 6 volumes of high activity accumulation immersed in the lower activity background. Each volume will feature different mean lifetime of ortho-positronium. Isotopes used for measurements must not only exhibit $\beta+$ activity, but also need to emit prompt gamma quanta (i.e. *Sc* or *Ga*) [1], [2]. In this contribution a method for controlling ortho-positronium lifetime is discussed along with preliminary results. In order to evaluate a method for the prepration of media with different ortho-positronium lifetime we have studied the ortho-positronium lifetime in water suspension of XAD4 porous material. XAD4 is characterized with the average pore size of 50 Å and can absorb water up to 60% of its mass [3]. Five samples of XAD4 with controlled amount of water were measured using PALS technique. Additionally one dry sample of XAD4 and one sample of pure water were measured. Obtained spectra were fitted with PALS Avalanche [4] and components corresponding to the ortho- positronium annihilation in XAD4 pores were established [5]. The results showed the correlation between the lifetime and production intensity of ortho-positronium and the concentration of XAD4 in water.

Motivation

New imaging method was developed by Jagiellonian PET collaboration that allows for simultaneous measurement of annihilation density distribution and positronium lifetime. Measurements of cardiac myxoma shown that ortho-positronium lifetime in cancerous tissue is different to that in healthy tissue. This phenomenon may be used to raise specificity of the imaging[6-9].

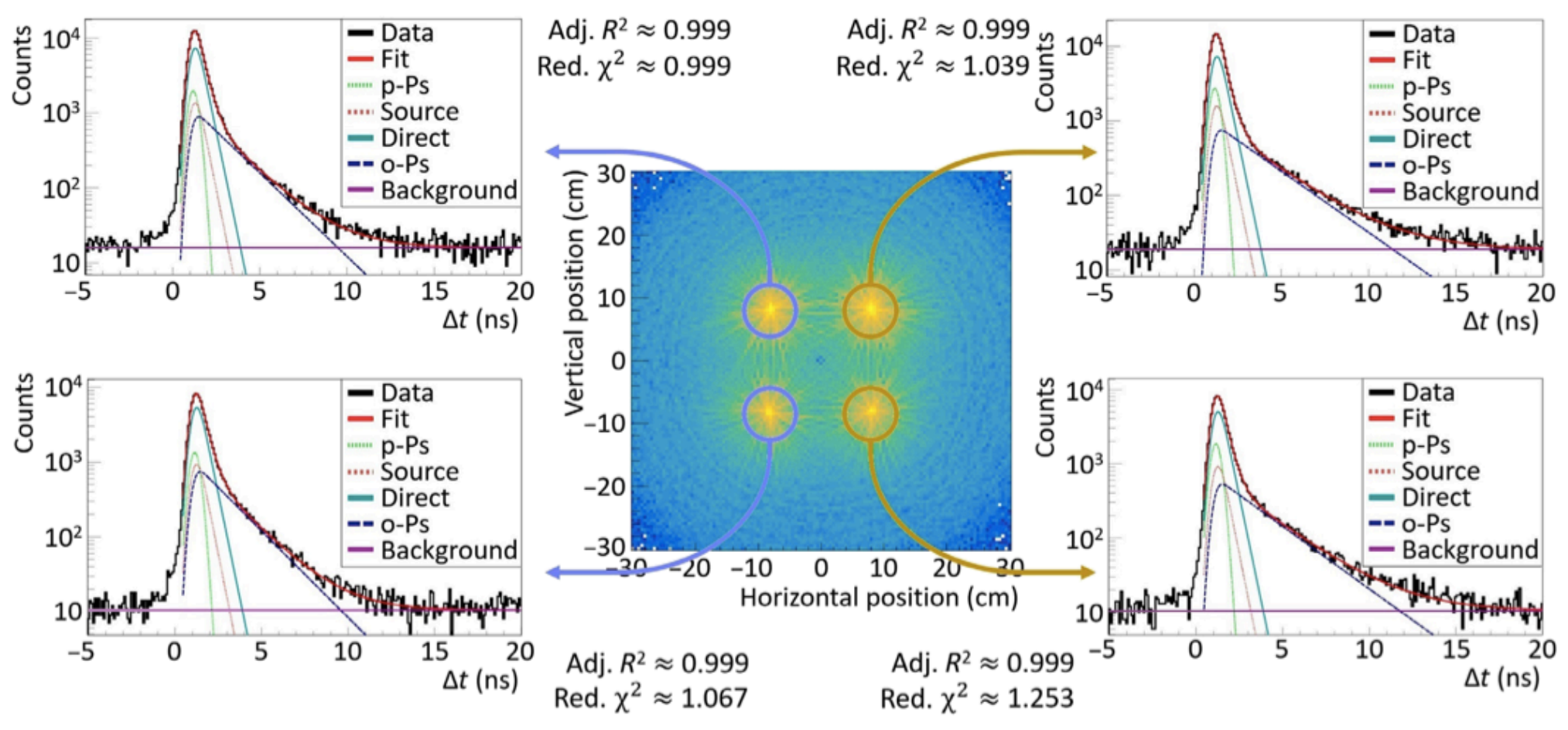


Fig. 2. SUV image with positronium lifetime images of experiment from *Positronium imaging with the novel multiphoton PET scanner* by P. Moskal et al., Science Advances 7 (2021)

^{22}Na isotope and ortho-positronium lifetime

Emitted positron together with an electron from surrounding matter may create a meta-stable atom called positronium. Positronium occures in two forms: para-positronium that lives 0,125 ns in vacuum, and ortho-positronium that lives 142 ns in vacuum and it's lifetime is observed to change depending on electron density of a medium. When ortho-positronium encounters electron it annihilates to two gamma quanta each with energy of 511 keV in process called pick-off shown schematically in Figure 3[10].

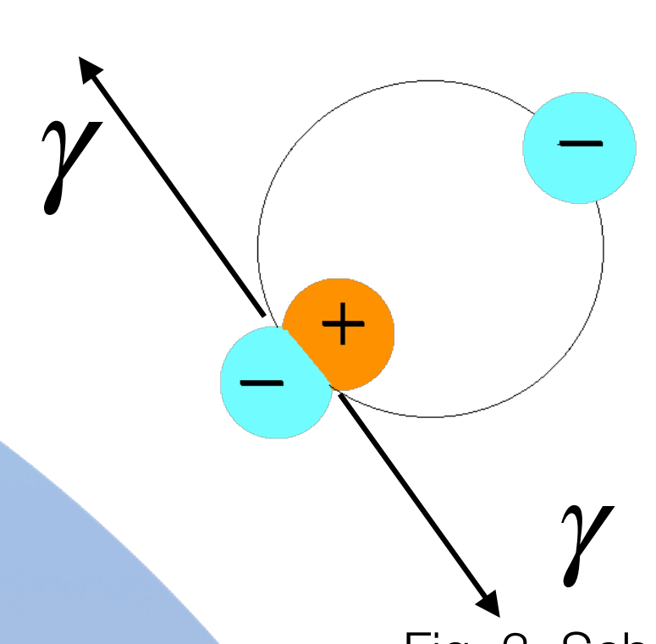


Fig. 3. Schematic representation of pick-off process.

The source of positrons used in experiments was ^{22}Na isotope, which undergoes $\beta+$ decays according to the decay scheme shown in Figure 4:

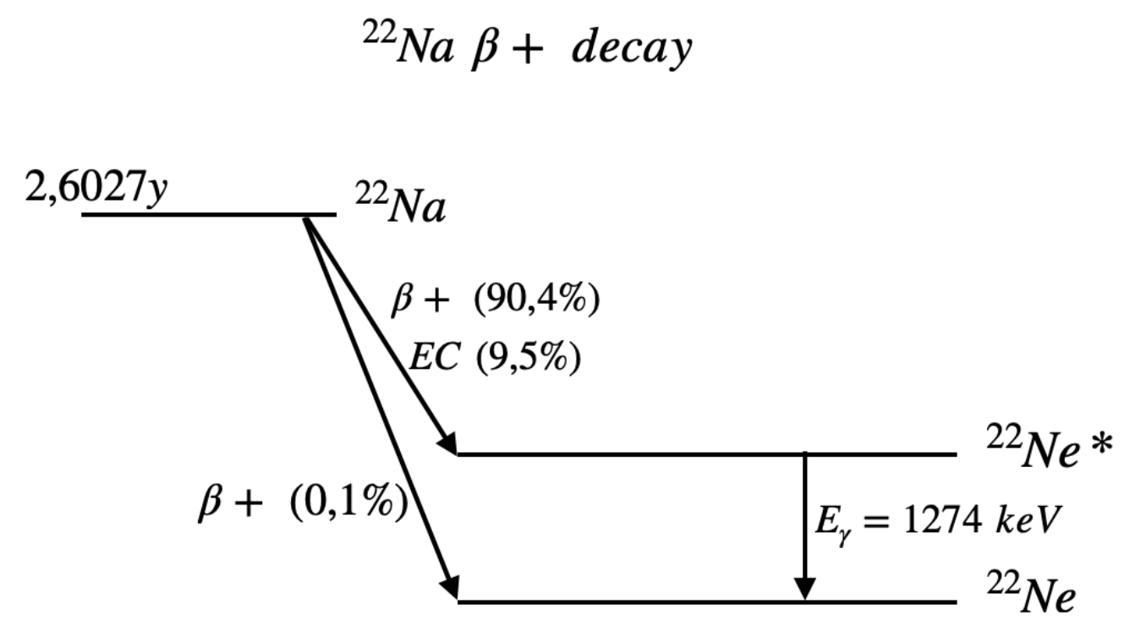


Fig. 4. ^{22}Na $\beta+$ decay scheme.

Ortho-positronium lifetime is measured as a time between registration of deexcitation gamma quanta and annihilation gamma quanta:

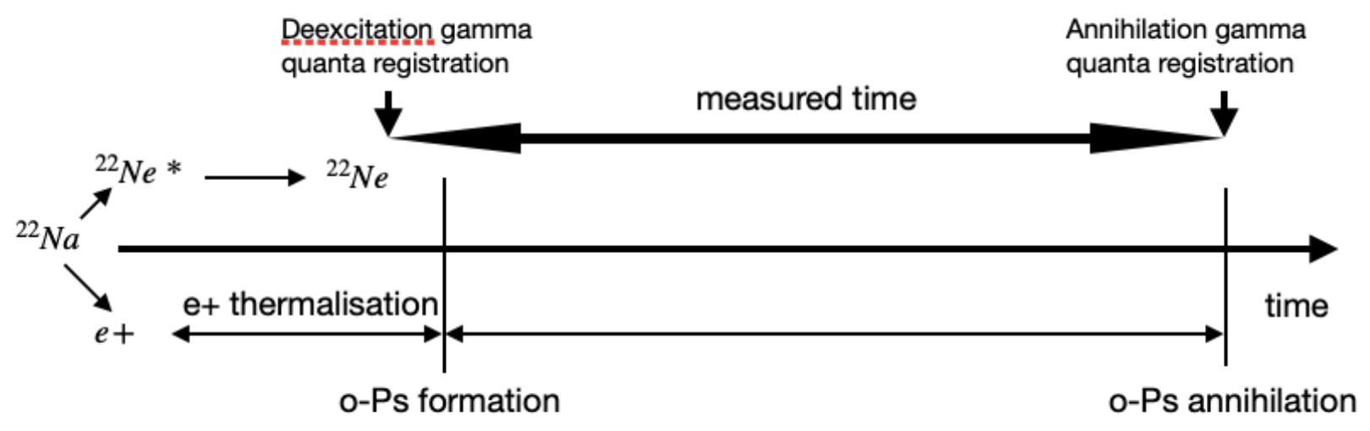


Fig. 5. The order of events used in positonium imaging. The timeline is not to scale.

Phantom proposal

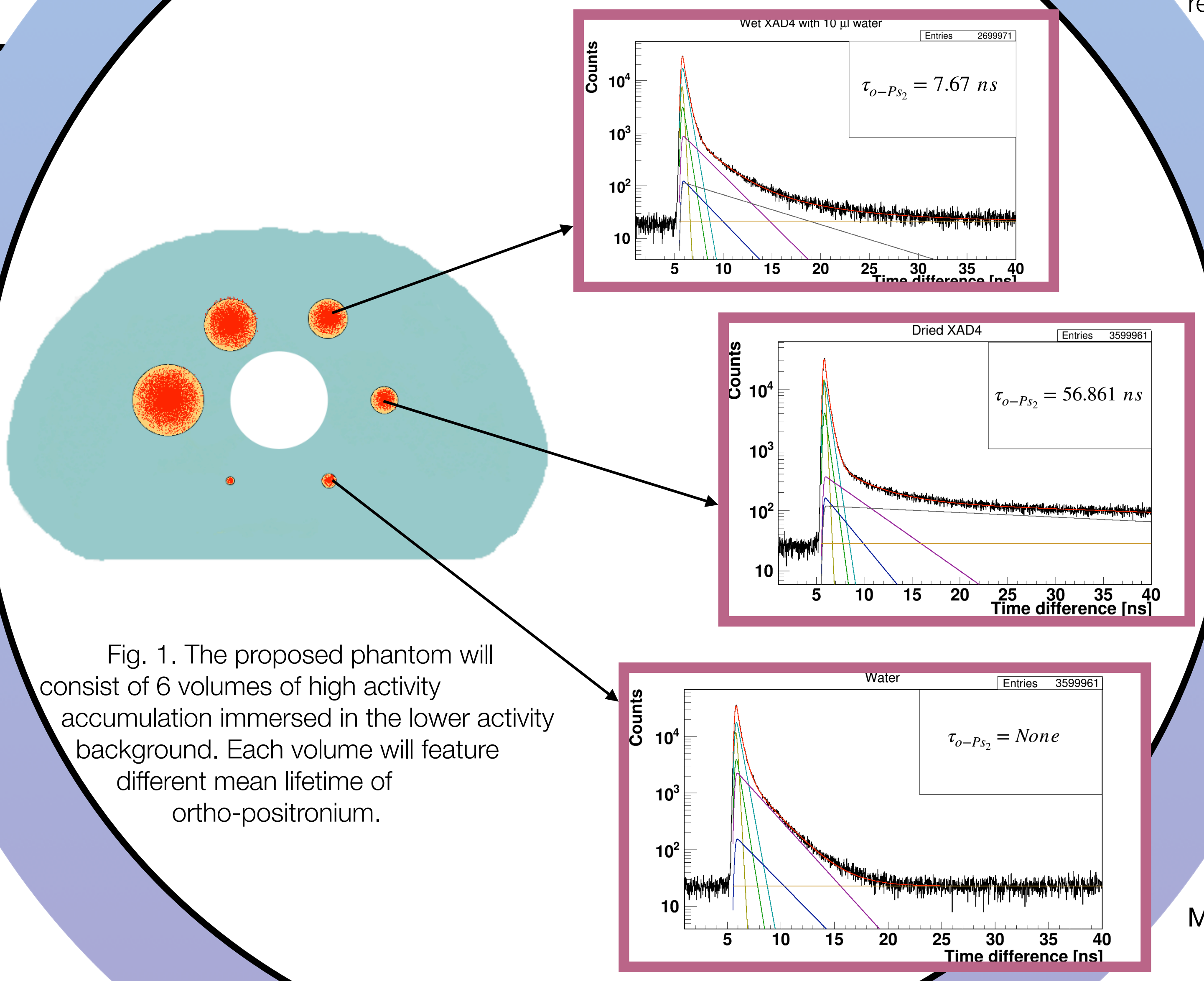
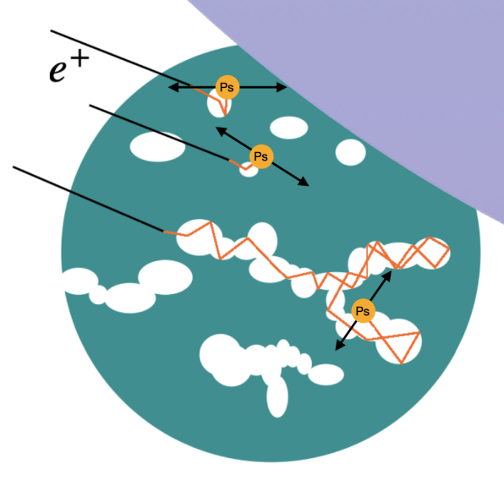


Fig. 1. The proposed phantom will consist of 6 volumes of high activity accumulation immersed in the lower activity background. Each volume will feature different mean lifetime of ortho-positronium.



Symbolic representation ofortho-positronium path in pores of XAD4.

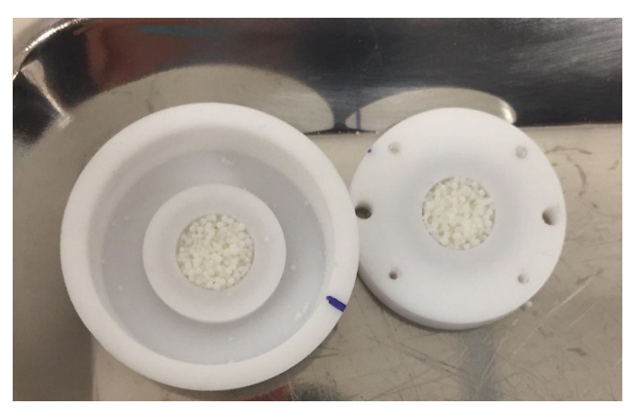


Fig. 8. Dry XAD-4 in teflon chamber.

The material (shown in Figure 8) used in this research was XAD-4: an hydrophobic resin in form of white beads with average pore diameter of 50 Å[3].

Experimental setup

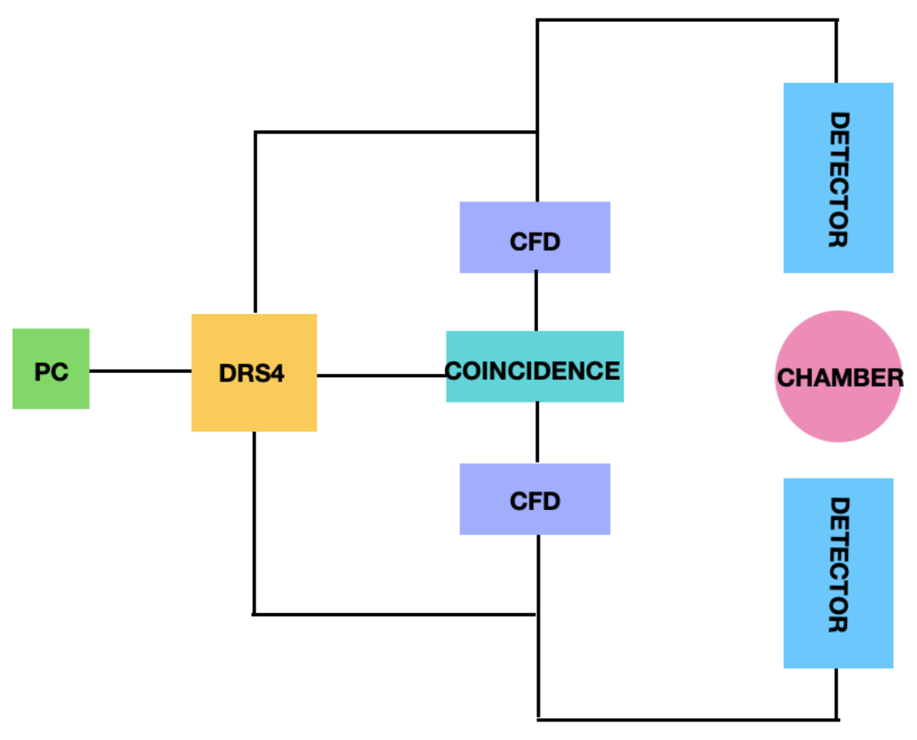


Fig. 6. Block scheme of experimental setup.

The experimental setup consisted of two detectors, each composed of BaF_2 scintillation crystal and photomultiplier. Signals were delivered to LeCroy 608C constant fraction discriminator, where different thresholds were applied to both signals. For detector registering deexcitation gamma quanta with energy 1274 keV signals with amplitudes > 70 mV, for detector registering annihilation gamma quanta signals with amplitudes > 14.5 mV were gathered. Signals passed to the coincidence module where coincidence window was set for 110 ns. Data was acquired using digitizer DRS4.

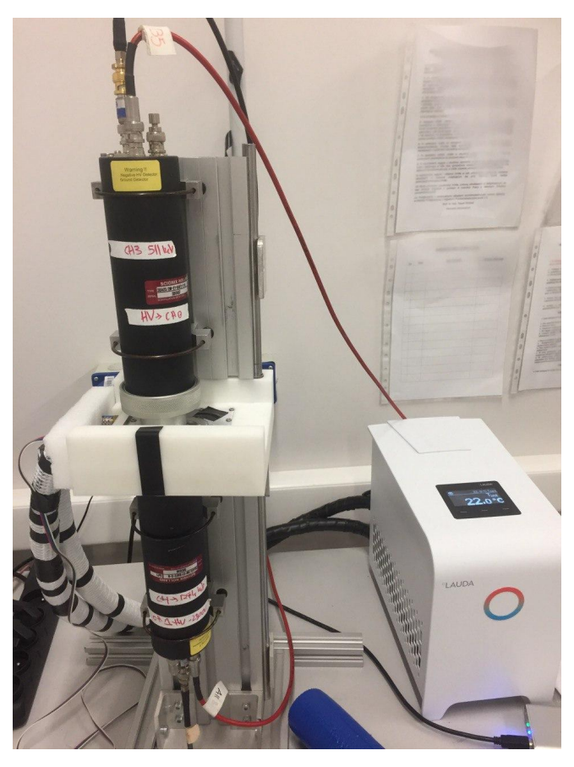
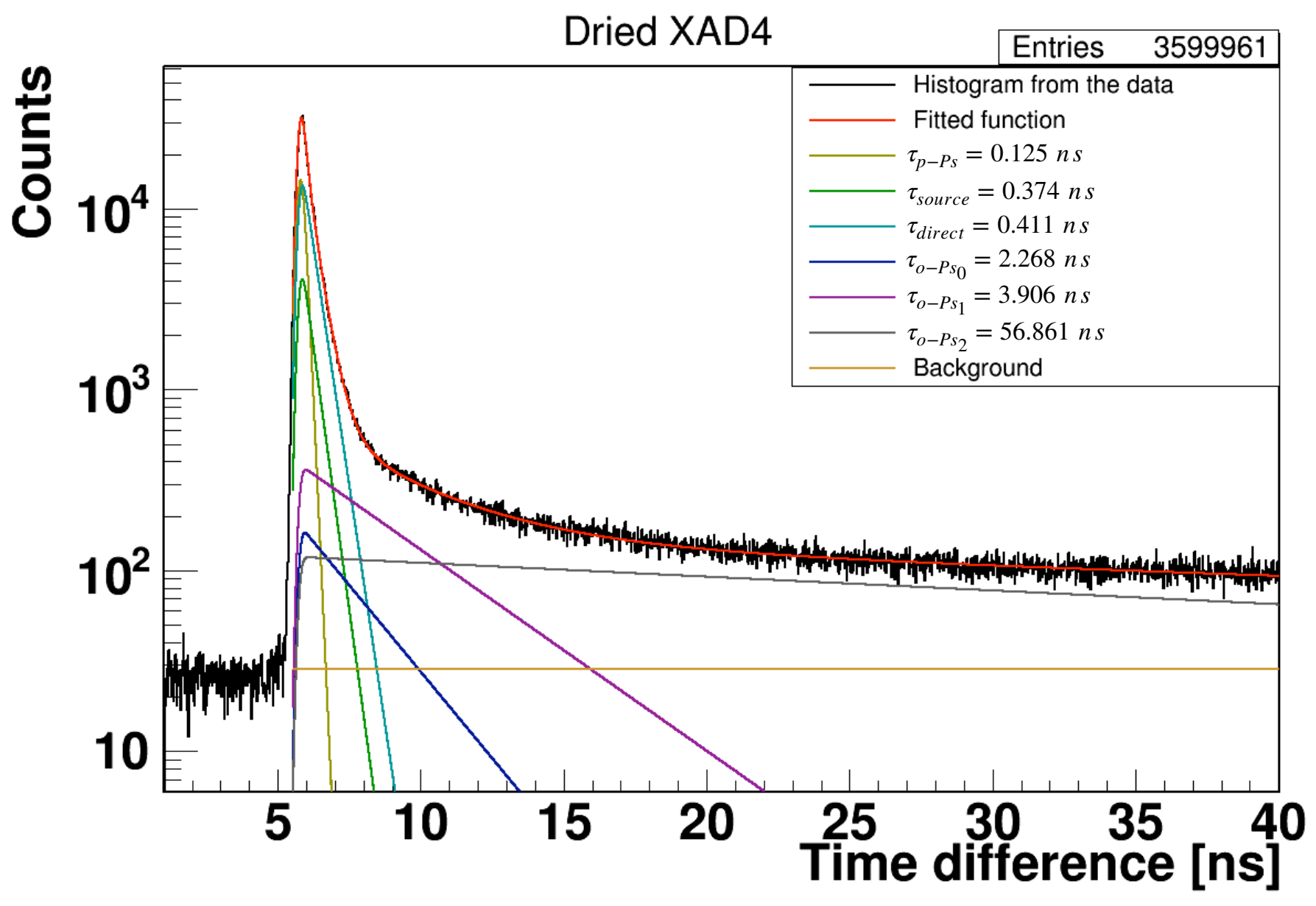


Fig. 7 Detectors and Lauda thermostat.



Acquired lifetime spectra (example in Figure 9) were fitted using PALS Avalanche program [4] with 6 components:

- 0.125 ns - para-pozytonium annihilation,
- 0.374 ns - positon annihilation in source,
- ~ 0.414 ns - positon annihilation in sample,
- 2.268 ns - ortho-positonium annihilation in parafilm,
- component 1 for ortho-positonium annihilation in XAD-4 pores,
- component 2 for ortho-positonium annihilation in XAD-4 pores.

Results

Mass percentage:

$$C_p = \frac{m_s}{m_s + m_r} \cdot 100\,\%$$

ms - substance mass
mr - solvent mass

Measurement	Mass percentage [%]	Lifetime for component 2 [ns]	Intensity for component 2 [%]	Chi^2/DoF
Water	0	0	0	1,35
Wet XAD-4 with 10 ul of water	43,6	7,67	0,0464	1,21
Wet XAD-4	46	15,1	0,0296	1,19
Dried XAD-4 with 40 ul water	67,3	37,3	0,131	1,27
Dried XAD-4 with 40 ul water	69,2	41,5	0,142	1,26
Dried XAD-4	100	56,9	0,263	1,27

The obtained results of lifetime and intensity dependance of long living component on mass percentage of XAD-4 in water is presented in Figures 10,11 below. The trend lines are preliminary as there is a need for further measurements to estimate statistical error of the measurement. Nevertheless there is correlation between **lifetime** of ortho-positonium in pores of XAD-4 and mass percentage of XAD-4 in water and there is correlation between **intensity** of component 2 and mass percentage of XAD-4 in water.

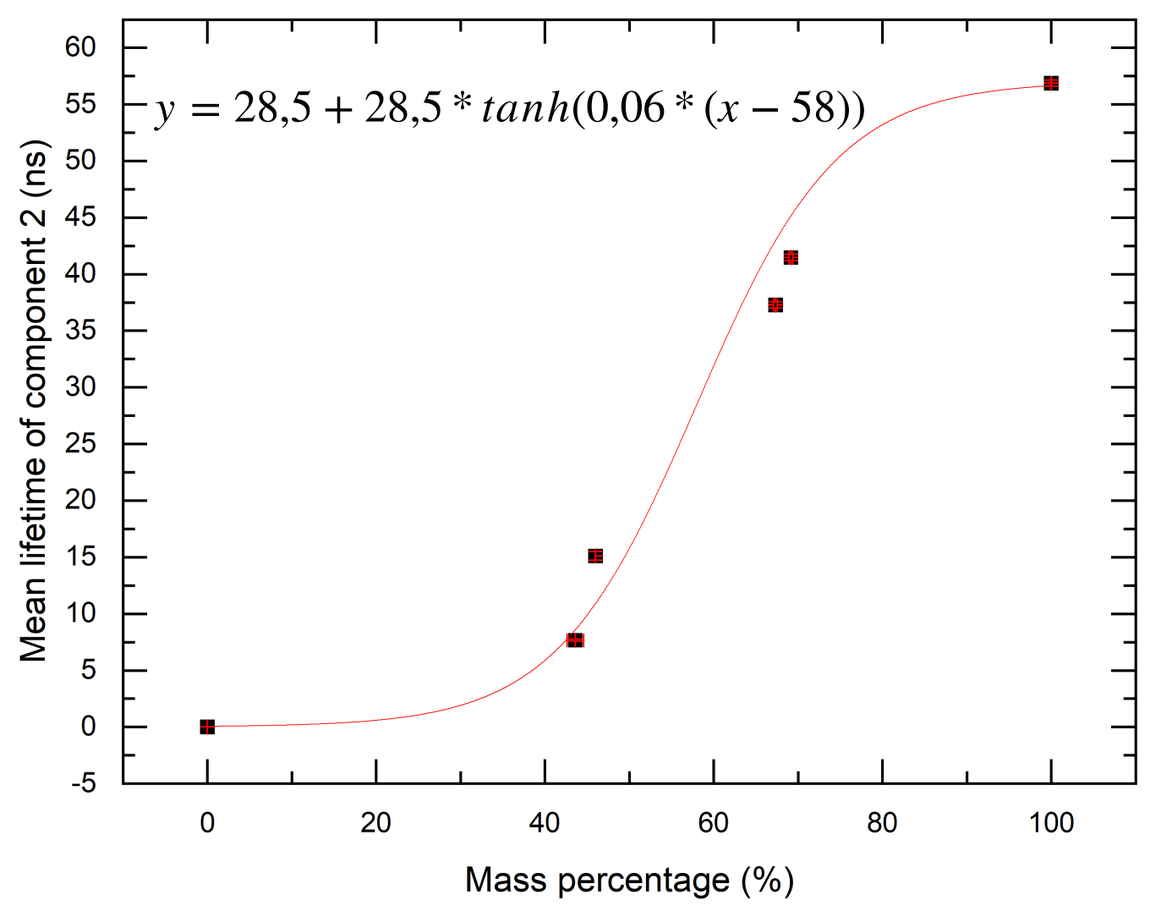


Fig. 10. Dependancy of mean lifetime of ortho-positronium for component corresponding to XAD4 pores on mass percentage of XAD4 in water. Trend line is drawn to guide the eye.

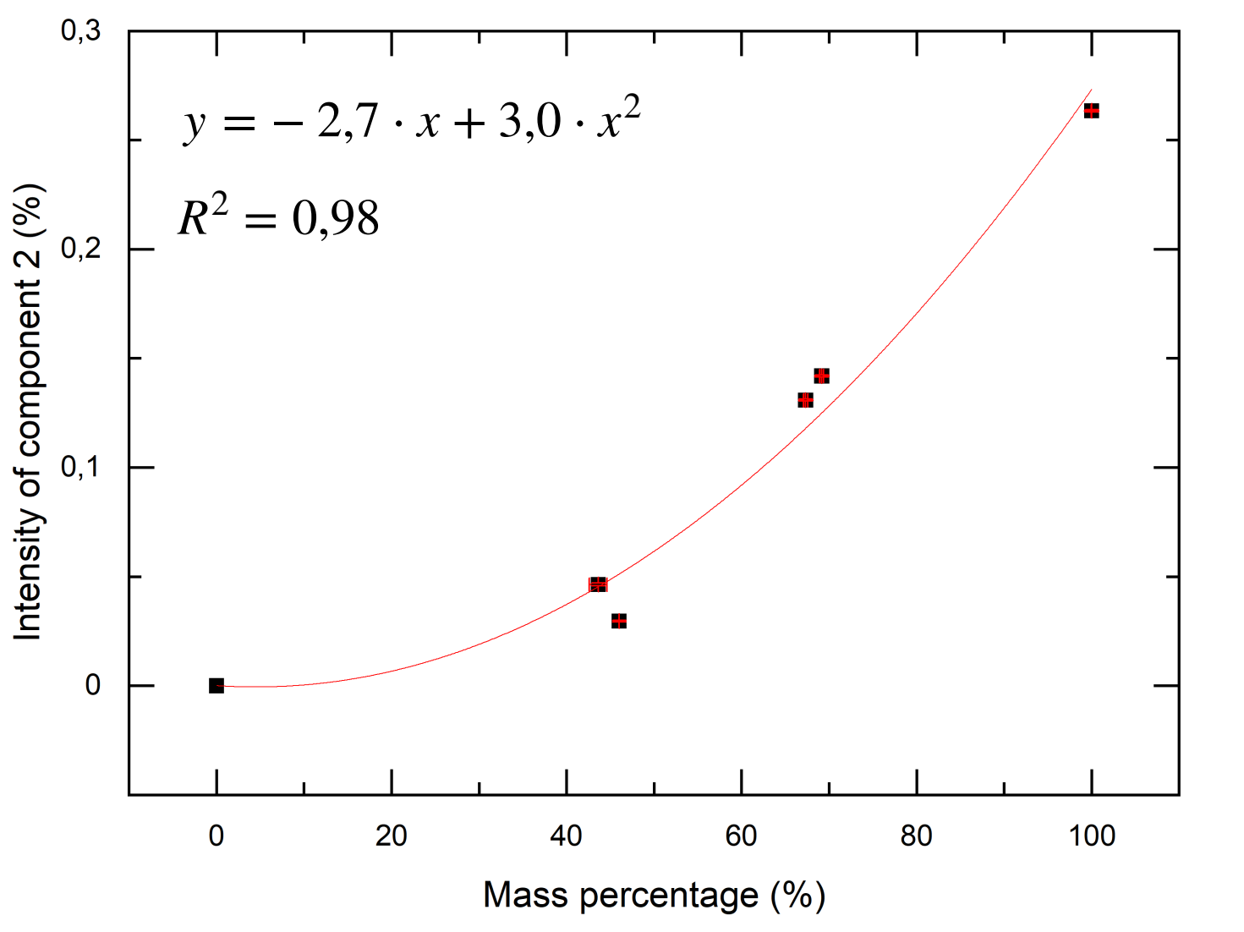


Fig. 11. Dependancy of intensity of component corresponding to XAD4 pores on mass percentage of XAD4 in water.

Summary

The results of the measurement show a correlation between the lifetime and production intensity of ortho-positronium and the concentration of XAD4 in water. This results can be used to create a NEMA-like phantom for measurements of ortho-positronium lifetime alongside activity concentration to determine the precision of the new imaging method developed by Jagiellonian PET collaboration. This method has a potential to enhance the specificity of PET diagnostics.

Acknowledgements

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