Ex-Vivo Positronium Lifetime Imaging with 44Sc using J-PET Scanner

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Introduction

Positronium Lifetime Imaging (PLI), an advanced extension of Positronium Emission Tomography (PET), is an emerging diagnostic modality [1,2,3]. It has potential to probe nano-scale environmental properties such as hypoxia, tumor microenvironment pathology by mapping the spatial distribution of Ps lifetime in biological tissues [4, 5, 6]. Despite the common consensus on its advantages and ongoing progress in adaptation of reconstruction algorithms and detector technology, PLI faces slow translation in clinical applications mainly due to two reasons: (1) measurement of nano-second positronium lifetimes requires fast gamma-ray detectors, and (2) new radioisotopes that provide both medically suitable half-life and high positron yield accompanying a prompt gamma signal for Ps lifetime estimation. The first in-vivo results on PLI of human brain was reported by J-PET collaboration using ^{68}Ga radioisotope [7]. However, the low prompt gamma yield of ^{68}Ga, only a ~1.34% prompt-γ branching ratio, poses challenges for accurate lifetime estimation due to limited statistics [8].

To address this, ^{44}Sc has emerged as a highly promising isotope for PLI [9], boasting an optimal decay profile: a clinically suitable half-life of 4.04 hours, an ultrashort de-excitation delay of 2.61 ps, and a 100% decay probability producing a single, high-energy (1157 keV) prompt gamma following positron emission [8].

In this work, we report the successful application of PLI using ^{44}Sc, performed with the state-of-the-art Modular J-PET tomograph, featuring trigerless data acquisition enabling simultaneous multiphoton detection [7].

Materials and Methods

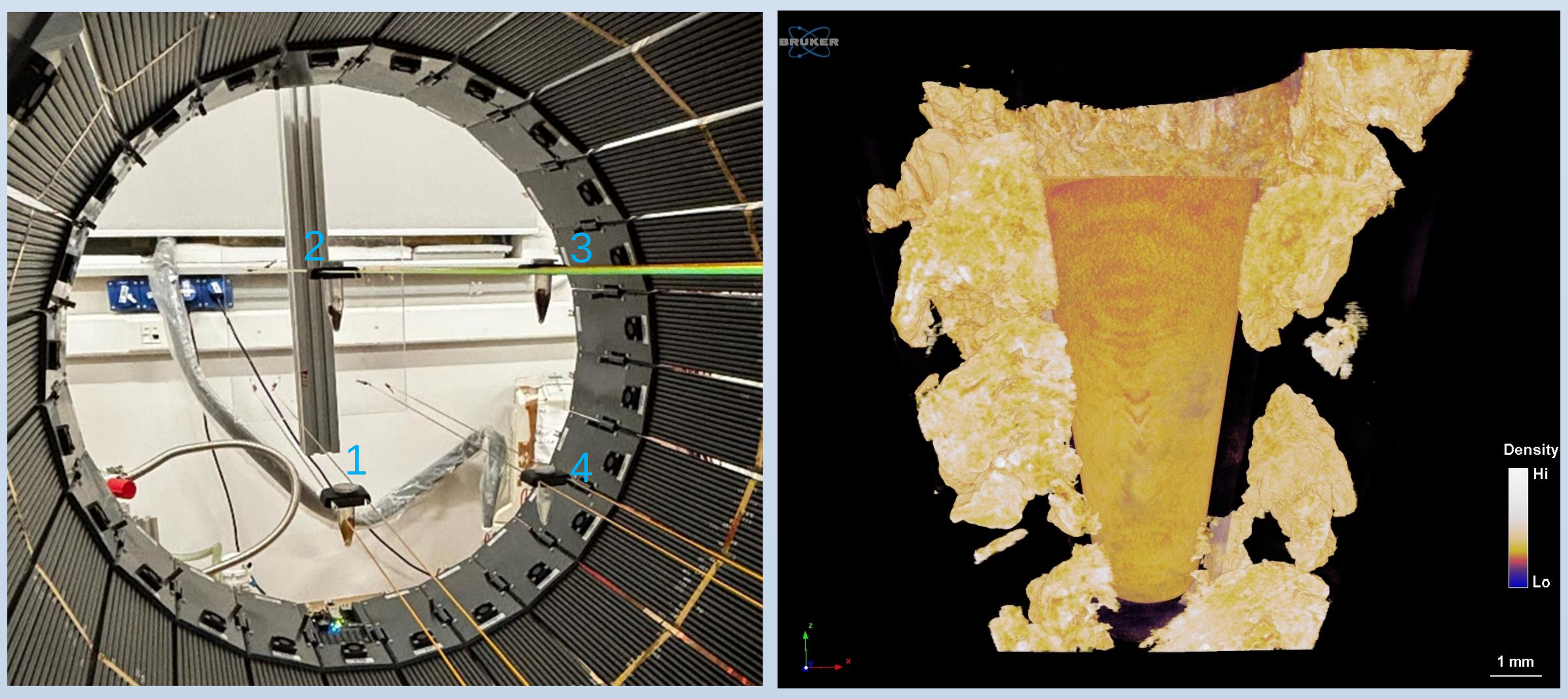

Figure 1. Scheme of sample setup in J-PET detector(L), Myxoma sample micro-CT image after experiment(R).

Setup consisted of 5 samples in total 4 phantoms shown on Fig. 1L and certified reference material made from fused silica[10]. Samples placed in phantoms are:

1. Adipose tissue
2. Cardiac myxoma tissue
3. Thrombin blood clot
4. XAD-4

Event selection was based on the simultaneous detection of two 511 keV photons and one de-excitation photon, enabling the reconstruction of positronium lifetime images. The reconstructed annihilation positions, obtained using the two 511 keV photons along with the positron lifetime, was used to identify regions of interest (ROIs) in image samples. Whereas the oPs lifetime was estimated utilizing the registration time of an additional prompt gamma as the o-Ps formation time. The obtained o-Ps lifetime shows good agreement with previously reported values for biological tissues [3, 11]. Lifetimes of positonium is callculted by fitting superposition of the convolution of Gauss and exponential functions.

$$y = y_0 + \frac{A_1}{t_1} * \frac{\exp\left(0.5 * \left(\frac{w}{t}\right)^2 - \frac{(x - x_c)}{t_1}\right) * \left(\operatorname{erf}\left(\frac{z_1}{\sqrt{2}}\right) + 1\right)}{2} + \cdots$$

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Results

Results obtained from 3h of measurement with J-PET modular system. Firstly from reconstructed position histograms with geometrical cuts presented in Tab. 1. lifetimes from interesting region is selected. After that lifetime histograms with bin width 0.2 ns is analyzed using Equation from Methods.

Table 1. Geometrical selection of lifetimes for samples.

	X plane cut [cm]	Y plane cut [cm]	Z plane cut [cm]	Real position [cm]
Adipose tissue	-11.8:-7.8	-13:-9	-5:5	-10;-10;0
Cardiac myxoma tissue	-12:-8	7.4:11.4	-5:5	-10;10;0
Thrombi blood clot	8:12	7.7:11.7	-5:5	10;10;0
XAD4	8:12	-12.3:-8.3	-5:5	10;-10;0
CRM (fused silica)	-12.5:-7.5	11.6:15.6	10:23	-10;14;15

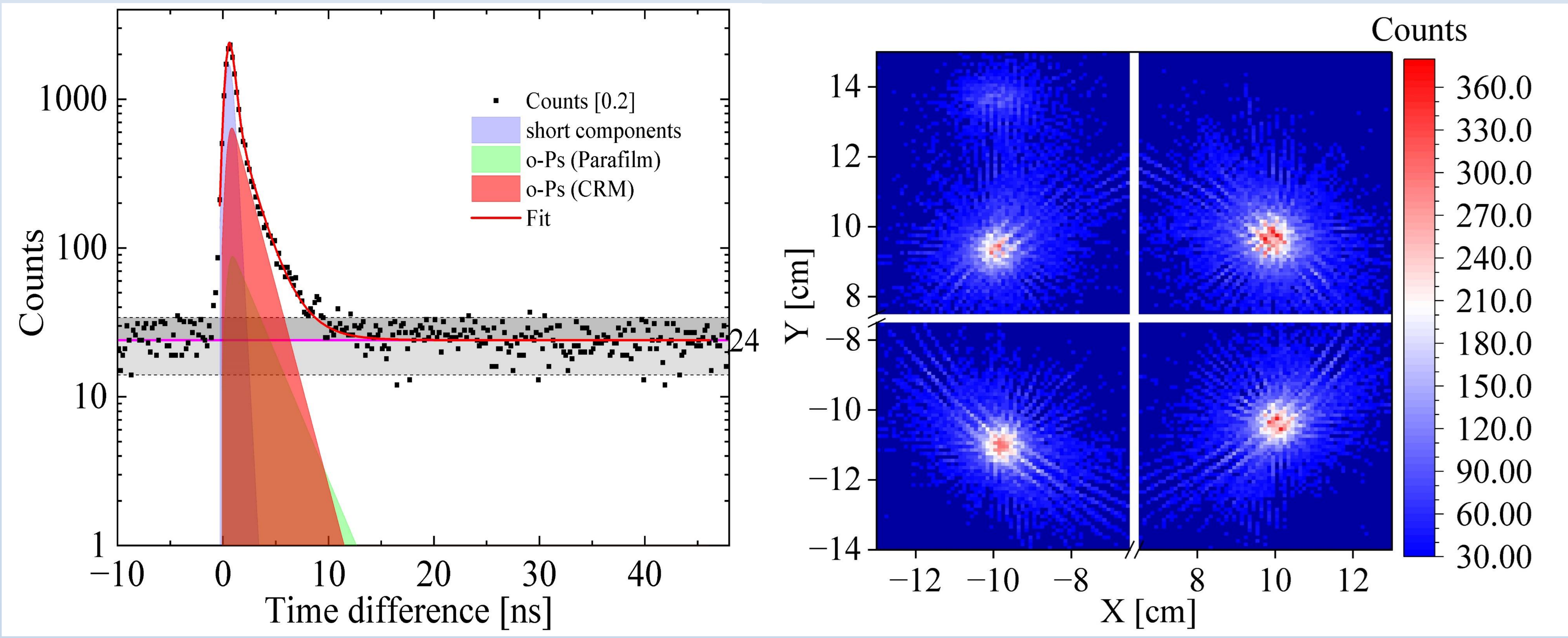

Figure 2. Time difference graph of CRM Sample (L), XY counts heatmap with 0.1 cm binwidth(R).

As quality control check yield correct o-Ps lifetime of fused silca with inesity 42%. The identification of positronium lifetime correlating with PCR tubes in which Scandium was placed resulted in 1.95 ns lifetime included in further analysis of samples. After performing analogical analysis for 4 phantoms in chosen ROI from Tab. 1.

We acquired results presented in Tab. 2.

Table 2. Results of analysis of lifetimes for phantoms.

Sample	Sigma [ns]	1st Intensity [%]	1st lifetime [ns]	2nd Intensity [%]	2nd lifetime [ns]	3rd Intensity [%]	3rd Lifetime [ns]	4th Intensity [%]
Adipose tissue	0.344(2)	8(2)	0.052(2)	71(2)	0.416(4)	8.2(1)	2.82(22)	12.5(1)
Cardiac myxoma tissue	0.345(1)	-	-	77.1(1)	0.389(5)	22.9(1)	1.96(5)	-
Blood clot	0.356(2)	23(2)	0.055(1)	55(2)	0.424(9)	11.9(7)	1.82(9)	10.4(2)
XAD 4	0.361(2)	24(2)	0.060(1)	55(2)	0.435(7)	5.7(4)	4.49(29)	14.7(5)

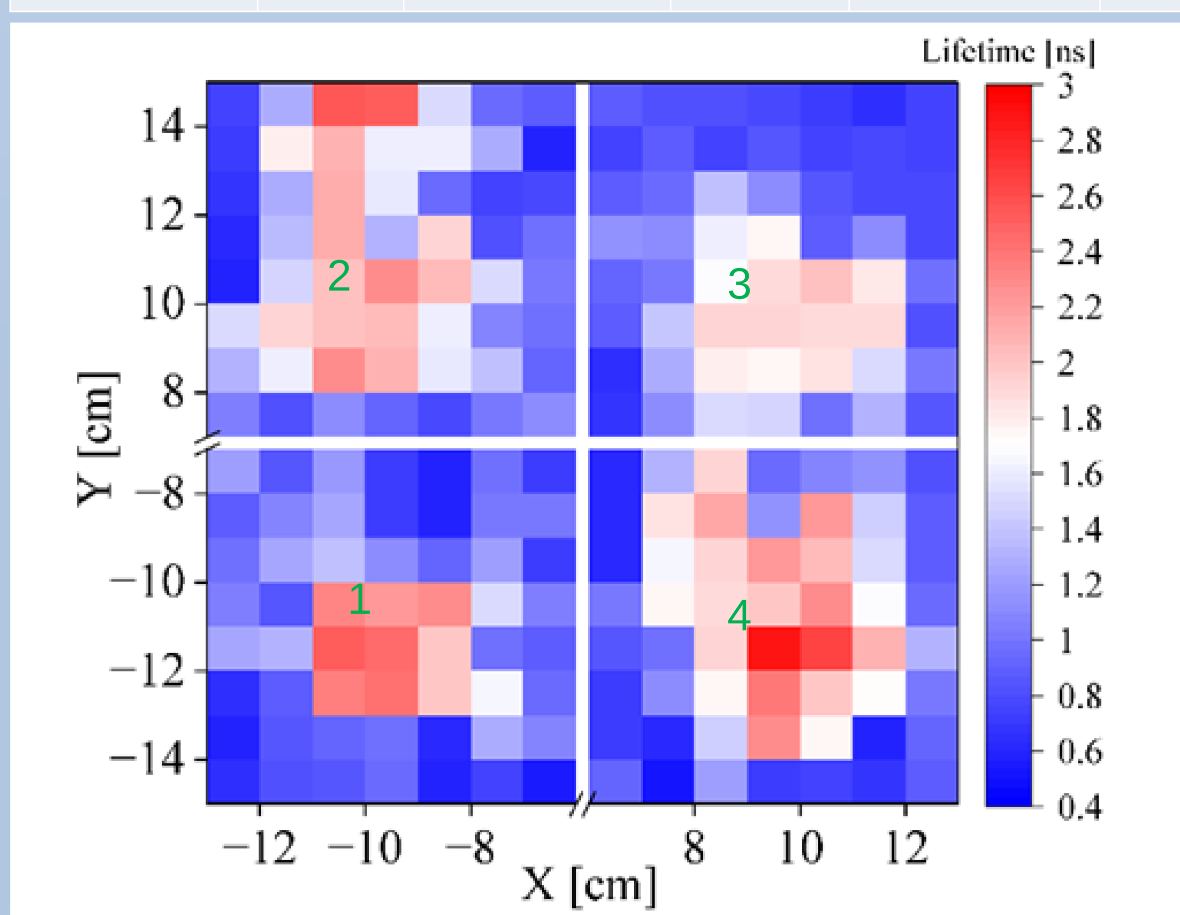

Fig. 3 give insight into possibilities of J-PET system in terms of PLI application however as the fitting check and manual interpretation is used in this experiment result this gives possibilities for implementation of the correct algorithm or even some machine learning solution to speed up the process and then lower the needed voxel size to minimum.

Figure 3. XY plane heatmap of o-Ps lifetimes for 4 phantoms and CRM material with 1 cm bins.

Conclusions

- In experiment four lifetime components are correctly identified.
- Capabilities of Modular J-PET allowed to recognize tissues from lifetimes after analysis.
- Proposed lifetime map shows great potential but need further development.
- Newly discovered parameters for biological parameters could be used similarly to MRS for PLI

J-PET

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