3γ tomography with J-PET

Daria Kisielewska
on behalf of the J-PET Collaboration

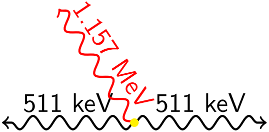
2nd Jagiellonian Symposium of Fundamental and Applied Subatomic Physics

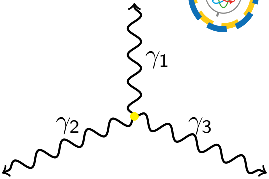
8 June 2017
Kraków

J-PET

JAGIELLONIAN UNIVERSITY
IN KRAKOW

3γ tomography





e^+e^- annihilation with additional photon from β^+ emitter deexcitation

- 2 annihilation photons are created back-to-back
- deexcitation photon momentum is independent
- the additional photon is used to increase imaging resolution

Ortho-positronium tomography with oPs $\rightarrow 3\gamma$ annihilation

- momenta of three photons created in o-Ps decay are co-planar
- ortho-positronium (o-Ps) lifetime in tissue strongly depends on inter-cellular spaces' size
- morphological imaging possible through determination of o-Ps lifetime[1]

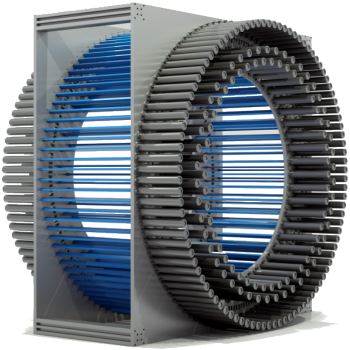
Material	No Ps formed[2]	Water[2]	IC3100[3]	XAD-4[3]
$f_{3\gamma} = \sigma_{3\gamma}/\sigma_{2\gamma}$	0.27%	0.52%	16.9%	28.9 %

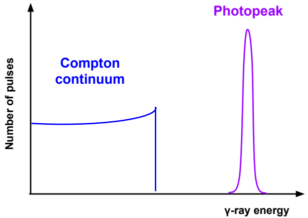
[1] A. Gajos, E. Czerwiński, D. Kamińska, P. Moskal, patent PCT/PL2015/050038

[2] *K. Merkurio et al.*, Phys. Med. Biol. **51**, N323 (2006)

[3] *B. Jasińska et al.*, Acta Phys. Polon. B **47**, 453 (2016)

J-PET detector

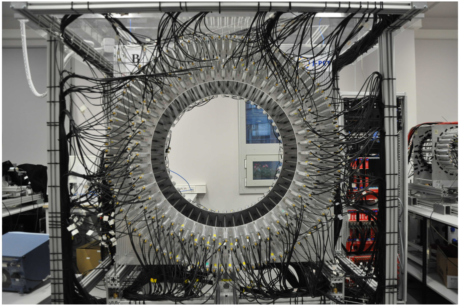


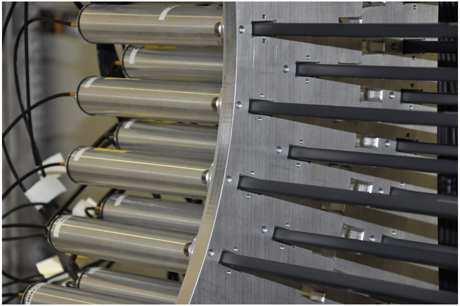


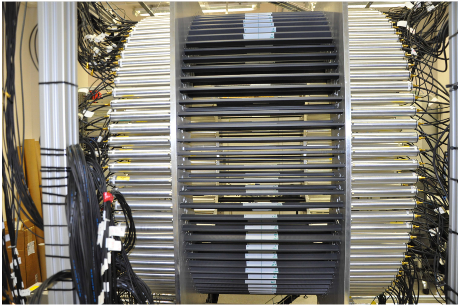
For a details see a talk by Sz. Niedźwiecki at Applied physics: Medical Applications, Monday

J-PET	Standard PET
Polymers	Crystals
Low granularity	High granularity
Low efficiency	High efficiency
High acceptance	Low acceptance
Compton scattering	Photoeffect
Time domain	Energy domain
Digital electronics	Analog electronics

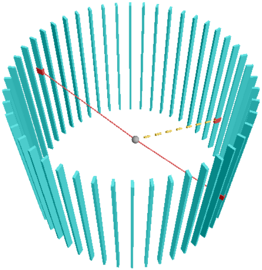
J-PET



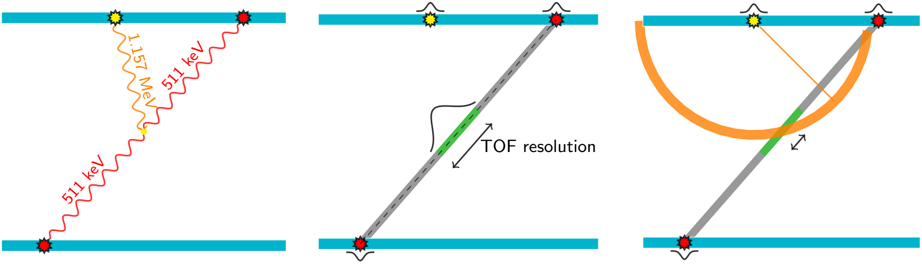




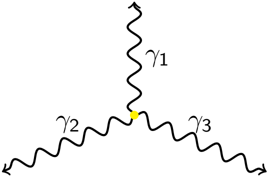
3γ-PET technique with the J-PET detector

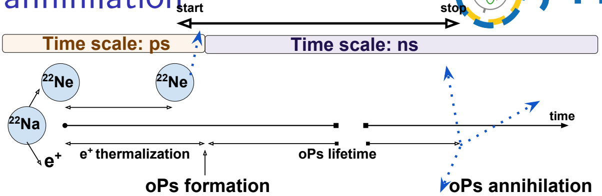


- Large acceptance offered by the J-PET apparatus allows for simultaneous recording of both annihilation photons as well as the deexcitation photon
- PET imaging resolution strongly depends on TOF resolution along the line of response (LOR)
- Information on the deexcitation photon can be used to improve resolution along LOR

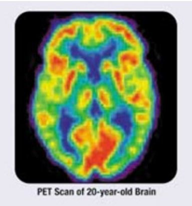


Ortho-positronium annihilation

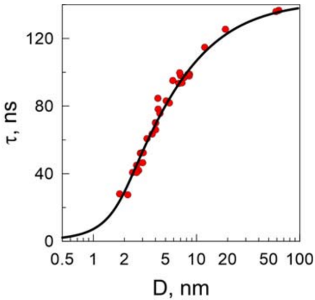




- Ortho-positronium (o-Ps) lifetime in tissue strongly depends on inter-cellular spaces' size
- The detection of 3γ annihilation photons carries information about the environment with which the positron interacts
- Morphological imaging possible through determination of o-Ps lifetime



www.web-books.com/eLibrary/Medicine/Appendix/PETscan.jpg



Comparison between o-Ps lifetime (τ) and a diameter of free volume (D). Solid line and red points shows theoretical prediction and experimental data, respectively. Figure is adapted from *R. Zaleski*, Nukleonika **60** 795 (2015)

Simulations

i) positron emission and thermalisation in the target material,

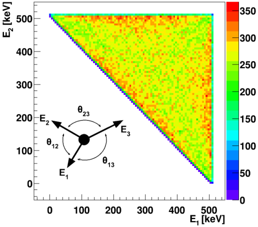
ii) angular and energy distributions of gamma quanta originating from ortho-positronium annihilation,

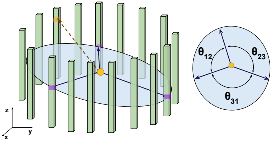
iii) Compton interactions of emitted gamma quanta in the detector built from plastic scintillators,

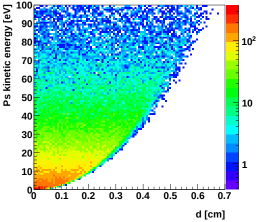
iv) determination of gamma quanta hit-position and hit-time in the detector with experimentally determined resolutions,

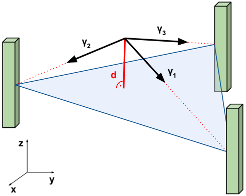
v) multiple scattering and accidental coincidences,

vi) reconstruction of registered gamma quanta fourmomenta



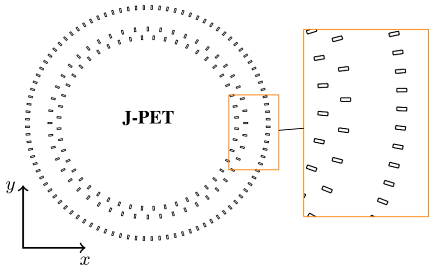


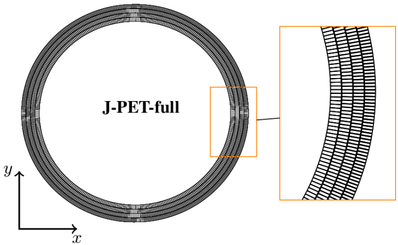




D. Kamińska et al. (J-PET) Eur.Phys.J. C76 (2016), 445

Simulations

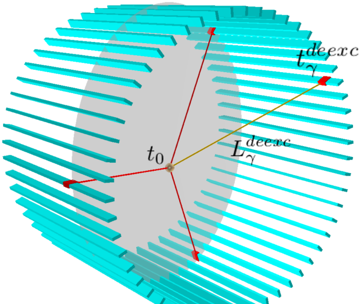




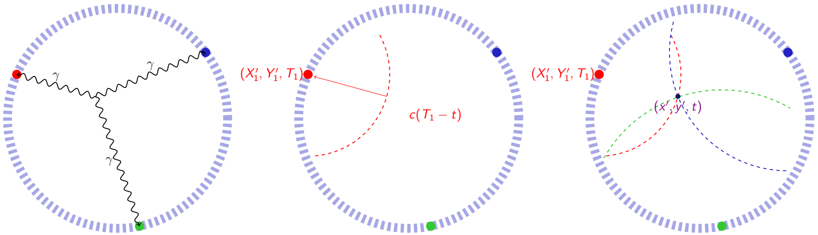
⇑ Geometry already build and tested

⇑ Simulated geometry

- momenta of the 3γ from o-Ps decay are contained within a single plane (in the o-Ps ref. frame)
- 4-th (deexcitaion) photon momentum is not correlated with the other three
- o-Ps $\rightarrow$ 3γ decay and deexcitation photon emission differ by distance and time related to free e^+ path and positronium life



Principle of o-Ps → 3γ reconstruction



A. Gajos et al. (J-PET) NIM **A819**, 54 (2016)

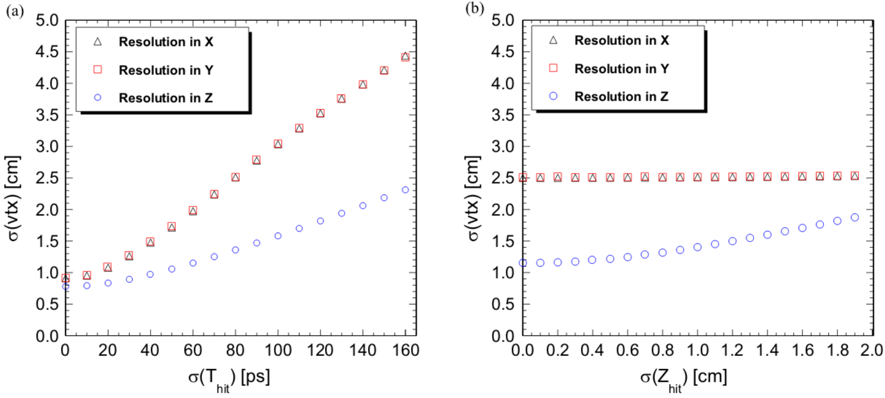
1. Find the decay plane containing the 3 hits in the J-PET barrel
2. Transform the hit coordinates to a 2D coordinate system in the decay plane $(X_i, Y_i, Z_i, T_i) \to (X_i', Y_i', 0, T_i')$
3. For each of the recorded γ hits define a circle of possible origin points of the incident photon assuming o-Ps decay at time t
4. Find the decay point (x', y') in the decay plane and time t as an intersection of 3 circles by solving the following equation system:

$$(T_i - t)^2 c^2 = (X_i' - x')^2 + (Y_i' - y')^2, \quad i = 1, 2, 3$$

   where: x', y', t - unknowns, T_i - time of i-th hit, X_i', Y_i' - coordinates of the i-th hit in the barrel expressed in the decay plane coordinates
5. Transform (x', y', t) of the decay point back to the detector 3D coordinate system

Spatial and time resolution of o-Ps decay point

The resolution of o-Ps decay obtained with the presented reconstruction method depends predominantly on the timing resolution of γ hits in scintillator strips.



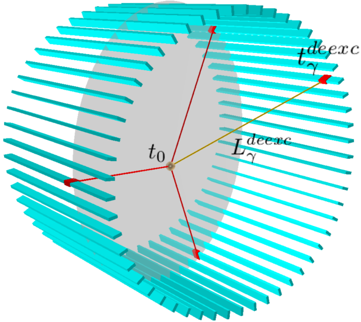
A. Gajos et al. (J-PET) NIM **A819**, 54 (2016)

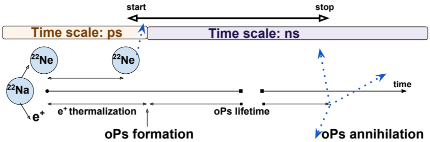
Ortho-positronium lifetime resolution

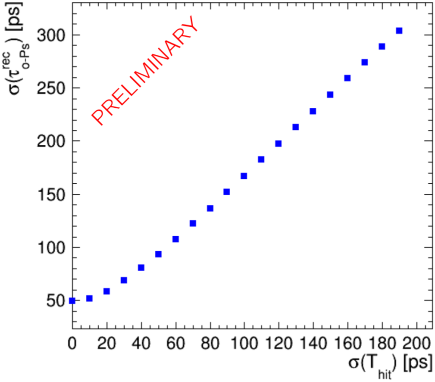
The ortho-positronium lifetime can be estimated as:

$$t^{rec}_{\text{o-Ps}} = t_0 - \left(t^{deexc.}_{\gamma} - \frac{L^{deexc.}_{\gamma}}{c} \right)$$

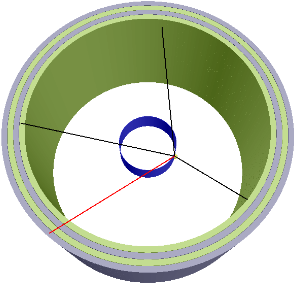
- t_0 - reconstructed o-Ps decay time
- $L^{deexc.}_{\gamma}$ - is calculated using reconstructed o-Ps decay point

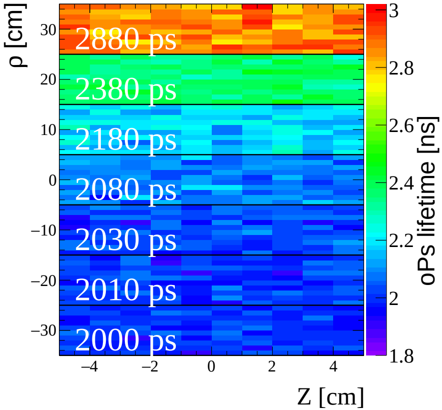




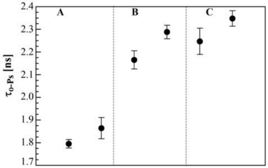


Morphological imaging



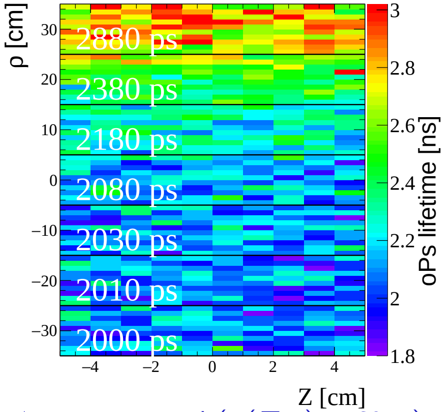


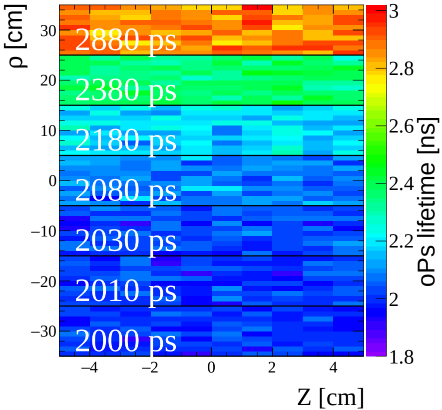
- cylindrically shaped β^+ emitter is localized in the center of the detector
- radioactive source is uniformly distributed along the cylinder
- ortho-positronium lifetime changes with the azimuthal angle
- values of oPs lifetime in plasma or hematocrits is within range 1.7-2.4 ns



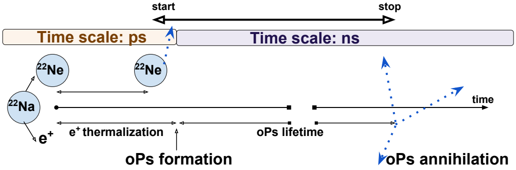
R. Zaleski, Nukleonika **58**, 199 (2013)

Morphological imaging





⇑ reconstructed $(\sigma(T_{hit}) = 60ps)$ ⇑ generated



Summary

- The J-PET detector can be used for multi-photon positron emission tomography imaging
- The standard TOF-PET spatial resolution can be improved by using information from de-excitation photon
- A novel imaging technique based on ortho-positronium annihilation into three-photons is based on the fact that the properties of ortho-positronium atom depend strongly on the size of the free volumes between molecules
- The latter technique may be used as an indicator of the stage of development of metabolic disorders

Thank you for your attention