Studies of the discrete symmetries in the decays of positronium

with J-PET tomograph

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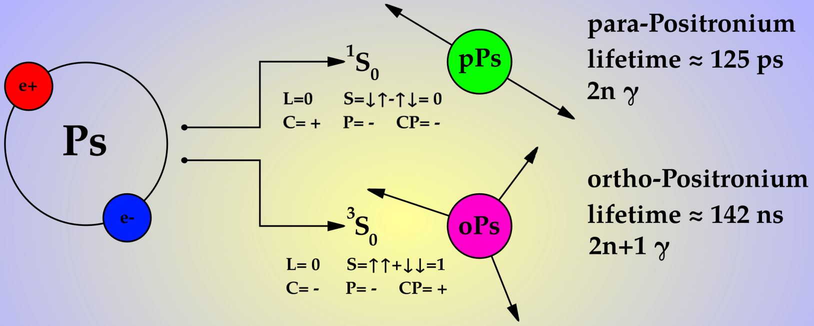
Outline

J-PET: P. Moskal et al. Acta Phys. Polon. B 47, 509 (2016)

- Positronium atom
- Symmetries studies
- J-PET
- Measurement methodology
- Event identification and background rejection
- Performed simulations and measurements
- Summary

Positronium atom (1)



- bound state of electron and positron - purely leptonic atom (and anti-atom at the same time)
- Eigen-state of P, C and CP operators $\mapsto$ good opportunity for symmetry breaking search

Positronium atom (2)

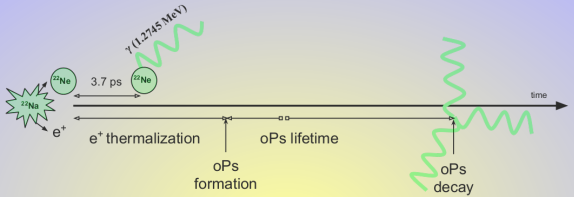
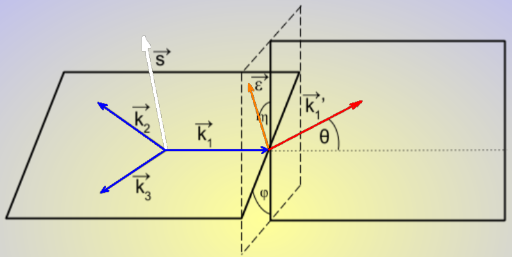


figure author: Daria Kamińska

- No symmetry breaking was observed in leptonic systems
- Best current experimental limits in leptonic systems:
  - **C**: $BR(pPs \to 5\gamma / pPs \to 2\gamma) < 2.7 \times 10^{-7}$ at 90% CL
    Phys. Rev. A 66, 052505 (2002)
  - **CP**: violation amplitude $< 4.9 \times 10^{-3}$ at 90% CL
    Phys. Rev. Lett. 104, 083401 (2010)
- **CPT**: decay asymmetry amplitude $C_{CPT} = 0.0071 \pm 0.0062$
  Phys. Rev. Lett. 91, 263401 (2003)

Symmetries studies (1)



J-PET: P. Moskal et al. Acta Phys. Polon. B 47, 509 (2016)

In **oPs** $\rightarrow 3\gamma$ decay we can measure:

momentum vectors of decay photons $\vec{k}_i$

momentum vectors of scattered photons $\vec{k'}_i$

vectors of polarization of photons $\vec{\epsilon}_i = \vec{k}_i \times \vec{k'}_i$

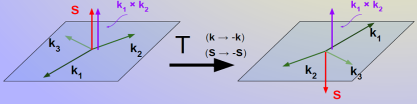
$\vec{S}$ **oPs** spin vector

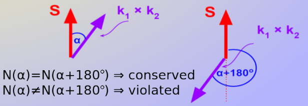
Symmetries studies (2)

J-PET: P. Moskal et al. Acta Phys. Polon. B 47, 509 (2016)

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	even	odd	even	odd	odd
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	even	even	odd	even	odd
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	even	odd	odd	odd	even
(new!) $\vec{k}_2 \cdot \vec{\epsilon}_1$	even	odd	odd	odd	even
(new!) $\vec{S} \cdot \vec{\epsilon}_1$	even	even	odd	even	odd
(new!) $\vec{S} \cdot (\vec{k}_2 \times \vec{\epsilon}_1)$	even	odd	even	odd	odd

Choose **odd-symmetry** operators. Example for $\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$ and **T**:

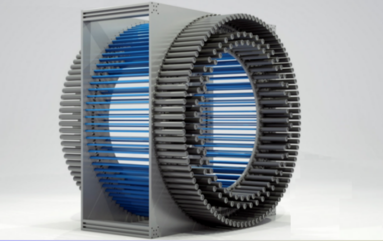


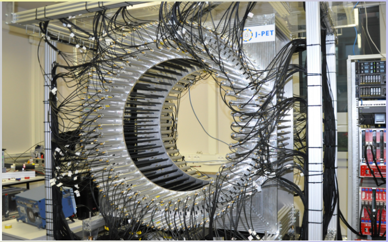


Jagiellonian Positron Emission Tomograph

J-PET Collaboration of over 30 people from 5 Institutions

www.koza.if.uj.edu.pl/pet

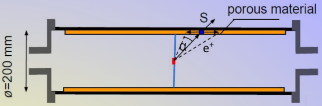


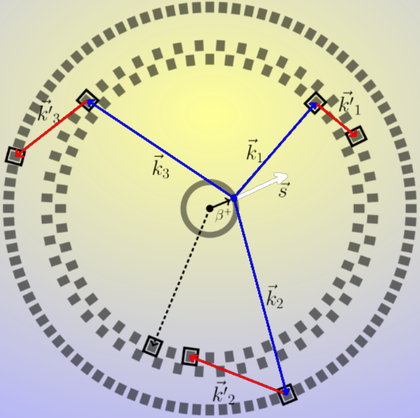


J-PET has over 15 patents and over 50 publications (selected below):

- A. Gajos et al., Nucl. Instrum. Meth. A819 (2016) 54
- D. Kamińska et al., Eur. Phys. J. C76 (2016) 445
- P. Moskal et al., Phys. Med. Biol. 61 (2016) 2025
- P. Moskal et al., Nucl. Instrum. Meth. A775 (2015) 54
- P. Moskal et al., Nucl. Instrum. Meth. A764 (2014) 317
- P. Moskal et al., Bio-Algorithms and Med-Systems 14, 7 2 73 (2011)

Measurement methodology



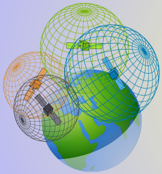


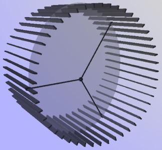
Event identification and background rejection

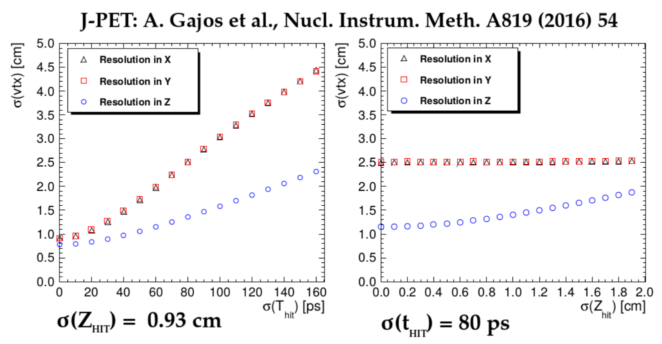
- **oPs** annihilation position reconstruction based on GPS-like algorithm
  J-PET: A. Gajos et al., Nucl. Instrum. Meth. A819 (2016) 54
- relative angles of photon momenta
  J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445
- Time over Threshold as measure of E_{dep}
  poster during 2^{nd} Jagiellonian Symposium on Fundamental and Applied Subatomic Physics

Annihilation position reconstruction

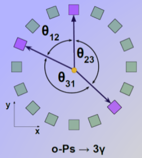
1. Transform from 3D coordinates to decay plane coordinates
2. Find intersection point of 3 circles by solving for (x, y, t):
$(T_i - t)^2 c^2 = (X_i - x)^2 + (Y_i - y)^2$, $i = 1, 2, 3 \rightarrow$ photon hits
3. Transform back to detector XYZ



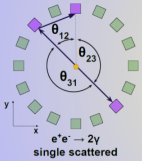




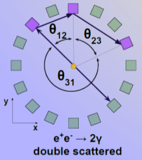
Relative angles of photon momenta (1)



$\theta_{23} > 180 - \theta_{12}$

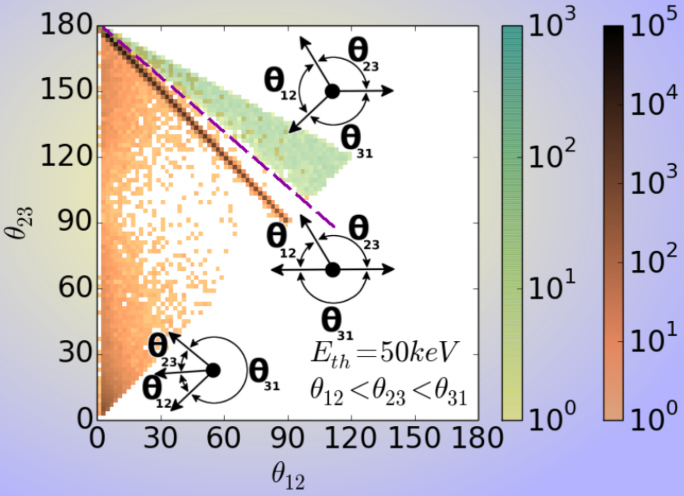


$\theta_{23} = 180 - \theta_{12}$

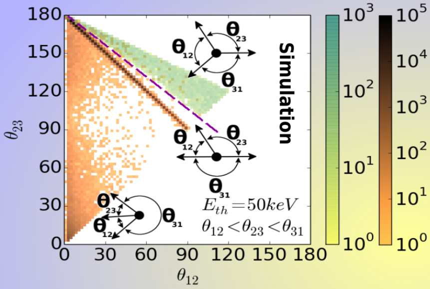


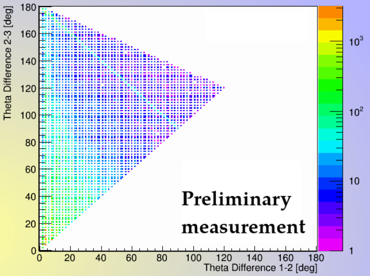
$\theta_{23} < 180 - \theta_{12}$

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



Relative angles of photon momenta (2)

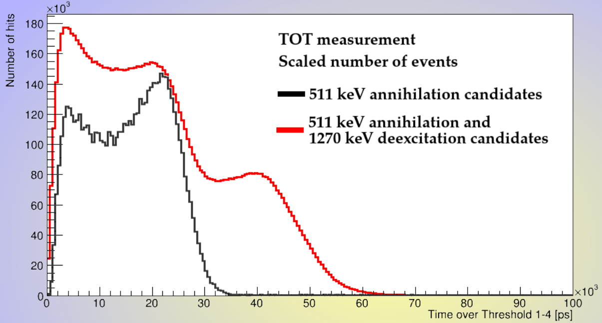


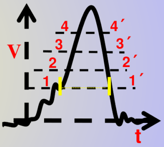


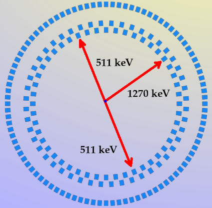
Monte Carlo simulation (left) from
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445
and result of measurement with annihilation chamber (right).

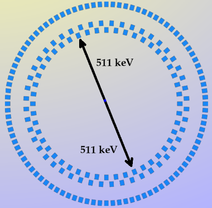
Reconstructed position of **oPs** annihilation and photon hit positions allows to obtain photons energy, based on energy and momentum conservation principle. For point-like positron source Monte Carlo simulation yields $\sigma(E_{hit}) = 4.1$ keV.

TOT as energy measure









Summary

Current status of work on J-PET project allows us to draw the following conclusions:

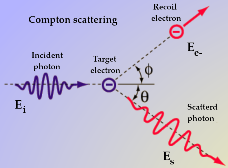
- J-PET is a suitable experiment to investigate discrete symmetries in positronium decays due to very good angle resolution and good time resolution
- well defined objectives of measuring expectation values of specific **C**, **P**, **T**, **CP**, **CPT** symmetry operators meet with capabilities provided by experiment design
- various methods and approaches to data simulation and reconstruction are being intensively developed by J-PET group
- preliminary results from initial data gathering runs are proving the potential of J-PET experiment

Quantum entanglement of oPs also can be detected using J-PET, as it was shown during 2^{nd} Jagiellonian Symposium on Fundamental and Applied Subatomic Physics presentation by Beatrix C. Hiesmayr, with the use of HMGH framework PRL 104, 210501 (2010)

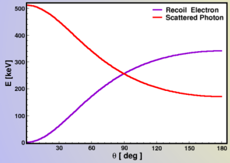
There is nothing more

Thank you for attention

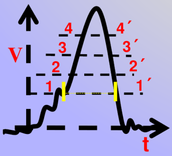
But wait! There are some backup slides



Energy deposited via Compton effect depends on incident photon energy and scattering angle:



$$E_{e^-} = E_i / \left(1 + \frac{E_i}{m_e c^2}(1 - \cos\theta)\right)$$
$$E_i = 511 \text{ keV}$$



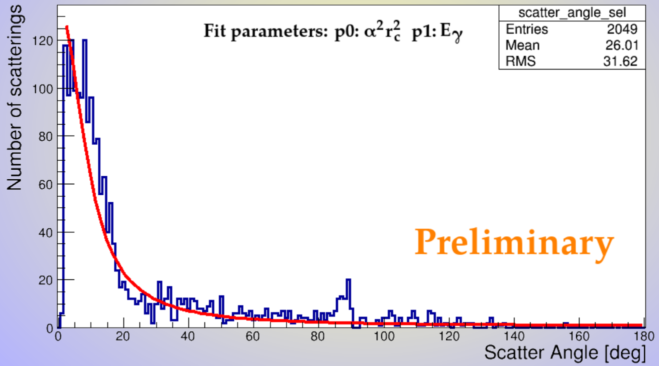
Measured value is Time over Threshold of registered signal in photomultiplier

$$TOT = \sum_{i=1}^{4} (t_i' - t_i)$$

Klein-Nishina

Klein-Nishina formula for differential cross-section of photon scattering

$\frac{d\sigma}{d\Omega} = \alpha^2 r_c^2 P(E_\gamma,\theta)^2[P(E_\gamma,\theta) + P(E_\gamma,\theta)^{-1} - \sin^2\theta]/2 \quad P(E_\gamma,\theta) = 1/(1+(E_\gamma/m_e c^2)(1-\cos\theta))$



Porous cylinder

First cylindrical porous target
by Prof. J. Goworek from UMCS