Efficiency estimates for various e^+e^- system decays

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Abstract

The Jagiellonian Positron Emission Tomography[1] detector is suitable to perform discrete symmetry tests[2] in positronium decays. The main aim of this research is to estimate the capability of the J-PET detector with respect to various positronium decay channels by means of Monte Carlo simulations with GATE[5][6]. Physics models of para- and ortho-positronia decays to 2, 3 and 4 photons together with the de-excitation gamma were implemented and corresponding simulations was performed. Two different geometrical configurations were taken into account: a three-layer setup corresponding to the current operating prototype and an upgraded version of a four-layer prototype. The obtained detection efficiency was used to determine preliminary experimental sensitivity estimates for several processes. The performed feasibility studies show that the J-PET detector can provide results competitive to the currently established experimental upper limits.

J-PET detector geometries and simulation system

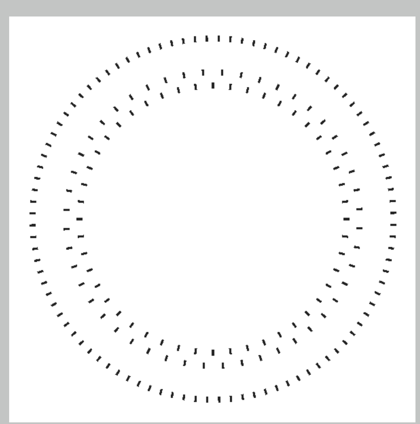

Table:
Three layers J-PET detector geometry parameters - current detector geometry.
Scintillators dimensions are:
19 mm x 7 mm x 50 cm (each one layer)

Layer	Radius [mm]	Scintillators number
1	425.00	48
2	467.50	48
3	575.00	96

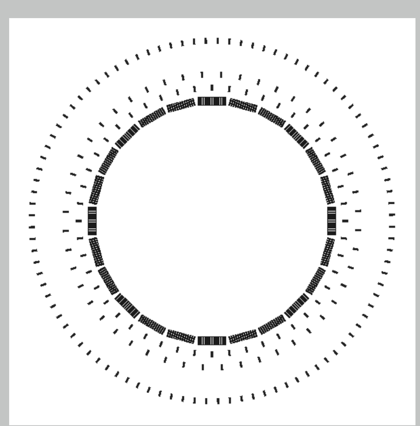

Table:
Four layers J-PET detector geometry parameters - prototype detector geometry.
Scintillators dimensions are:
6 mm x 25 mm x 50 cm (1st layer)
19 mm x 7 mm x 50 cm (2nd, 3rd and 4th layer)

Layer	Radius [mm]	Scintillators number
1	381.86	24 x 13
2	425.00	48
3	467.50	48
4	575.00	96

Method

Discrete symmetries[4] can by tested by presented operators[3] :

Operator	$\mathcal{C}$	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{CP}$	$\mathcal{CPT}$
$\vec{S}\cdot\vec{k_1}$	+	-	+	-	-
$\vec{S}\cdot(\vec{k_1}\times\vec{k_2})$	+	+	-	+	-
$(\vec{S}\cdot\vec{k_1})(\vec{S}\cdot(\vec{k_1}\times\vec{k_2}))$	+	-	-	-	+
$\vec{k_2}\times\vec{\epsilon_1}$	+	-	-	-	+
$\vec{S}\cdot\vec{\epsilon_1}$	+	+	-	+	-
$\vec{S}\cdot(\vec{k_2}\times\vec{\epsilon_1})$	+	-	+	-	-

The **detection efficiency** for a given decay channel is defined as:

$$\epsilon_{det} = \frac{N_{det}}{N_{total}}$$

The **detection sensitivity** is given by:

$$\eta = \frac{K}{\epsilon_{det}\cdot N_{gen}}$$

Current experimental limits

Test of $\mathcal{C}$ symmetry
Current experimental upper limits for the decays forbidden by the $\mathcal{C}$ symmetry are:
BR($oPs\to 4\gamma/oPs\to 3\gamma$) $< \mathbf{2.6\times 10^{-6}}$ at **90%** CL [7], BR($oPs\to 5\gamma/oPs\to 3\gamma$) $< \mathbf{10^{-6}}$ at **90%** CL [7].
BR($pPs\to 3\gamma/pPs\to 2\gamma$) $< \mathbf{2.8\times 10^{-6}}$ at **68%** CL [8], BR($pPs\to 5\gamma/pPs\to 2\gamma$) $< \mathbf{2.7\times 10^{-7}}$ at **90%** CL [9].
Tests of $\mathcal{CP}$ symmetry
Current experimental upper limits for the $\mathcal{CP}$ symmetry violation in the ortho-positronium decay is $\mathbf{4.9\times 10^{-3}}$ at **90%** CL [10]. SM predictions for the vacuum polarization effects that would mimic the $\mathcal{CP}$ symmetry violation are of order of $\mathbf{10^{-9}}$ [10, 11].
Tests of $\mathcal{T}$ symmetry
So far no experimental results has been reported for the $\mathcal{T}$ symmetry tests in the positronium system.
SM predictions for the photon final state interaction that would mimic the $\mathcal{T}$ violation are at the level of $\mathbf{10^{-9}}$ [10, 11].
Tests of $\mathcal{CPT}$ symmetry
Current experimental upper limits for the $\mathcal{CPT}$ symmetry violation in the ortho-positronium decay is **0.3%** [12].
SM predictions for the radiative correction terms that would mimic the $\mathcal{CPT}$ violation are at the level of $\mathbf{10^{-9}}$ [11].

References

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Results

Each photon scattered at least once				
	E_{thr} = 50 keV		E_{thr} = 70 keV	
Decay channel	3 layers	4 layers	3 layers	4 layers
$^{22}Ne^* \to {}^{22}Ne + \gamma_{prompt}$	$1.4\cdot 10^{-2}$	$5.4\cdot 10^{-2}$	$1.4\cdot 10^{-2}$	$5.4\cdot 10^{-2}$
$pPs\to 2\gamma$	$3.9\cdot 10^{-3}$	$2.2\cdot 10^{-2}$	$3.3\cdot 10^{-3}$	$1.9\cdot 10^{-2}$
$oPs\to 3\gamma$	$1.9\cdot 10^{-5}$	$8.7\cdot 10^{-4}$	$9.2\cdot 10^{-6}$	$4.3\cdot 10^{-4}$
$Ps\to 4\gamma$	$1.5\cdot 10^{-7}$	$1.7\cdot 10^{-5}$	$2.0\cdot 10^{-8}$	$2.8\cdot 10^{-6}$
Each photon scattered at least twice				
	E_{thr} = 50 keV		E_{thr} = 70 keV	
Decay channel	3 layers	4 layers	3 layers	4 layers
$pPs\to 2\gamma$	$2.8\cdot 10^{-5}$	$7.2\cdot 10^{-4}$	$1.4\cdot 10^{-5}$	$3.6\cdot 10^{-4}$
$oPs\to 3\gamma$	-	$1.4\cdot 10^{-6}$	-	$6.0\cdot 10^{-8}$

Table: Efficiency for decay channels. Energy threshold is 460 keV for prompt gamma with initial emission energy equal 1274 keV.

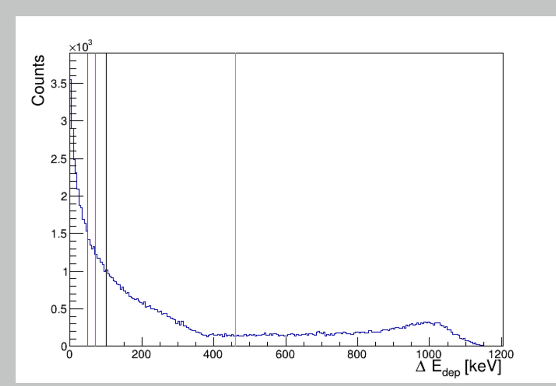

Figure:
Energy deposition of photons from oPs decay and from prompt gamma during first scattering.
Cuts: 50 keV (red line), 70 keV (purple line), 100 keV (black line) and for prompt gamma is 460 keV (green line).

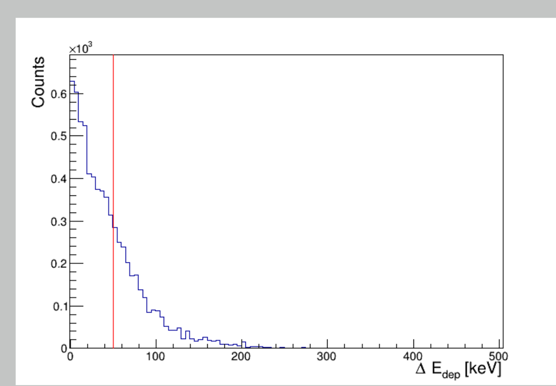

Figure:
Energy deposition of photons from oPs decay during second scattering - energy threshold is 50 keV.

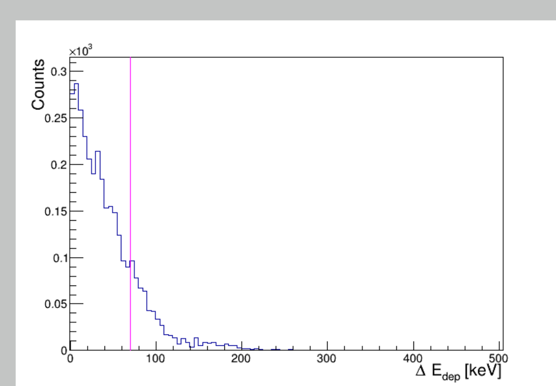

Figure:
Energy deposition of photons from oPs decay during second scattering - energy threshold is 70 keV.

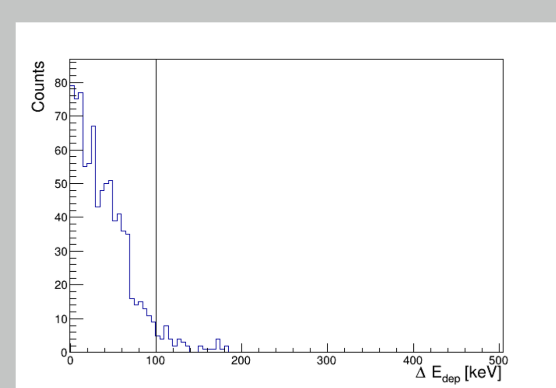

Figure:
Energy deposition of photons from oPs decay during second scattering - energy threshold is 100 keV.

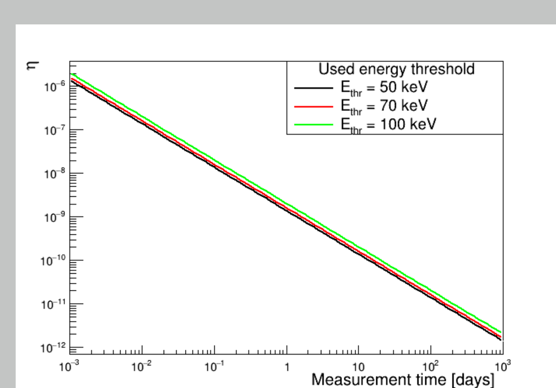

Figure:
Experimental sensitivity η for decay $pPs\to 2\gamma$.
Each gamma scattered minimum once.

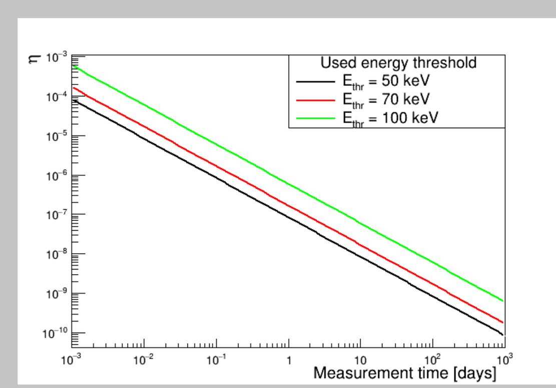

Figure:
Experimental sensitivity η for decay $oPs\to 3\gamma$.
Each gamma scattered minimum once.

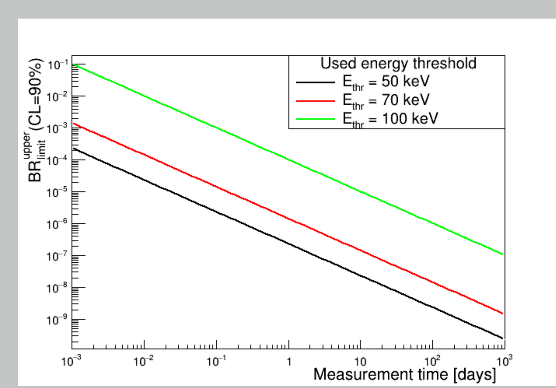

Figure:
Branching ratio for channel decay $pPs\to 4\gamma$.
Each gamma scattered minimum once.

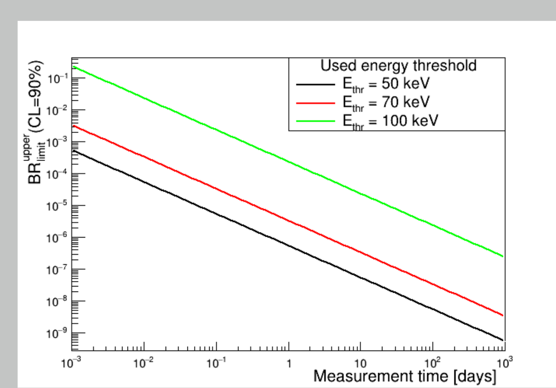

Figure:
Branching ratio for decay $oPs\to 4\gamma$.
Each gamma scattered minimum once.

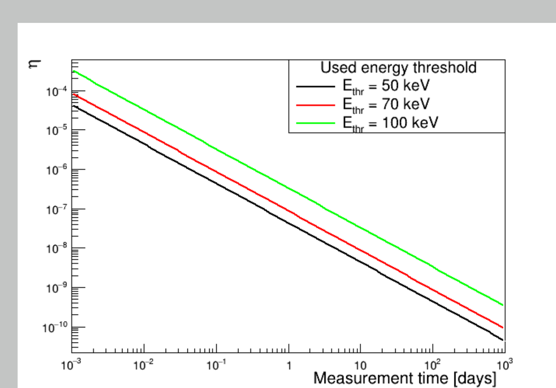

Figure:
Experimental sensitivity η for decay $pPs\to 2\gamma$.
Each gamma scattered minimum twice.

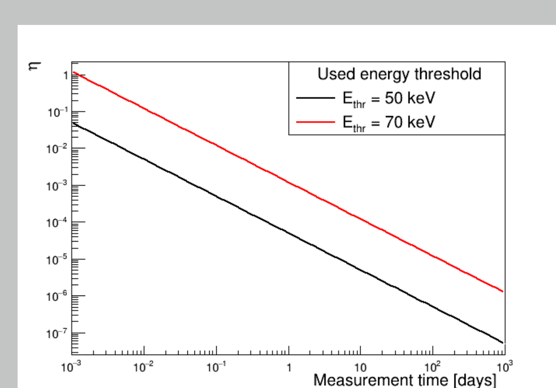

Figure:
Experimental sensitivity η for decay $oPs\to 3\gamma$.
Each gamma scattered minimum twice.

Conclusions

The established detection efficiency ortho-positronium decay into three-gamma with prompt photon shows that the J-PET can easily overcome the current existing limit for the $\mathcal{CP}$ violation and provide the competitive results for the $\mathcal{CPT}$ tests. The analysis of the positronium decay into 4 gammas channels, show that the $\mathcal{C}$-symmetry conservation tests together with the SM allowed rare decays can be performed at the J-PET especially with the new four-layer geometry. The obtained results should be complemented by the careful background studies. It is worth to mention, that the new modular design of the detector, allows to configure several geometrical setup, that can even further enhance the experimental sensitivity of the J-PET scanner.