Precision test of discrete symmetries in the decays of positronium atoms using the J-PET detector

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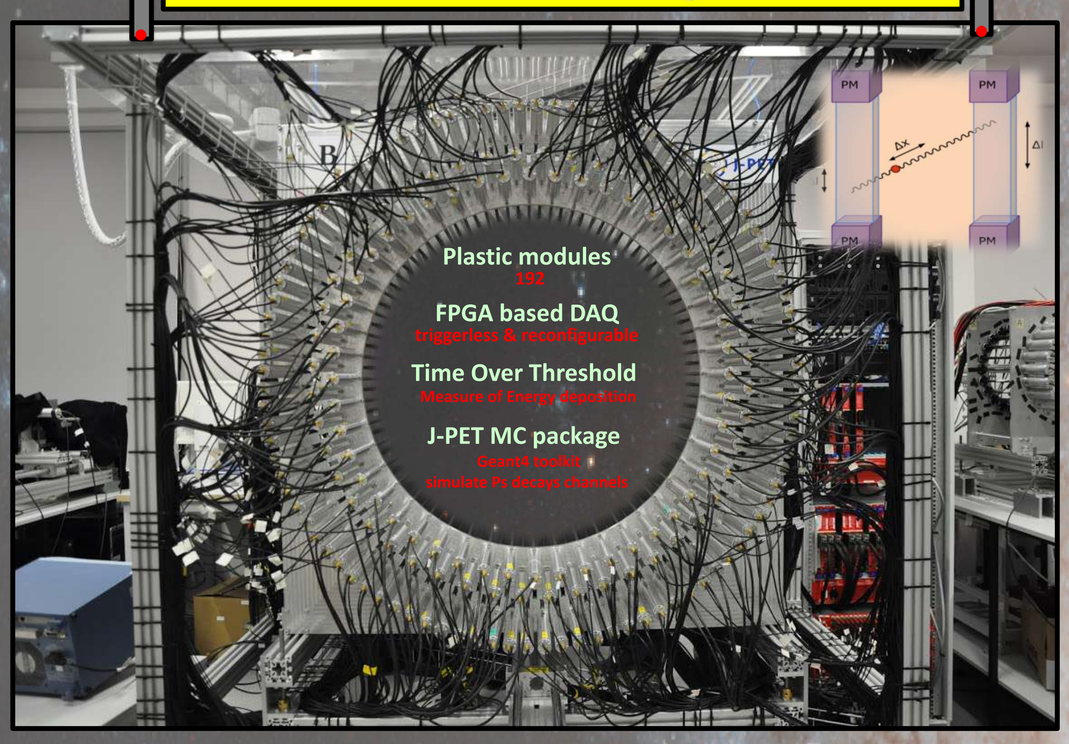
Introduction

- Positronium is a unique laboratory to study discrete symmetries whose precision is limited, in principle, only by the effects due to the weak interactions expected at the level of 10^{-14} [1] and photon - photon interactions expected at the level of 10^{-9} [2].
- Violation of T or CP invariance in purely leptonic systems has not been observed yet [3].
- The experimental limits on CP and CPT symmetry violation in the decays of positronium atom are set at the level of 10^{-3} [4,5] and limits on charge conjugation violation are set at the level of 10^{-7} [6-8].
- Thus, there is still a margin of six orders of magnitude as regards T and CP, and two orders of magnitude as regards the C symmetry, where the phenomena beyond the Standard Model can be sought for by improving the experimental precision in investigations of decays of positronium atoms.
- ☑ The Jagiellonian Positron Emission Tomograph (J-PET) is constructed of 192 polymer scintillators placed in three consecutive cylindrical layers of diameter 85, 93.5 and 115 cm respectively [9-15].
- ☑ The capability of ***registering multi-photons*** originating from the **decays of positronium atoms** enables to ***perform tests on discrete symmetries***.

J-PET Facility



Annihilation chambers

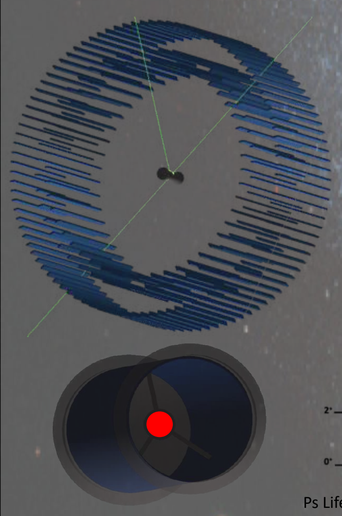
Small chambers

Cylindrical chamber

Spherical chamber

J-PET Monte Carlo Package (Geant4)

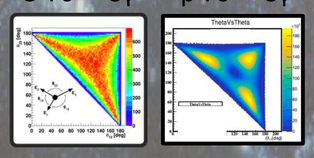
Geometry



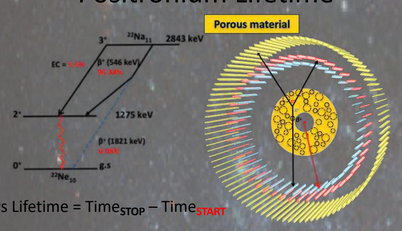
Physics

Positronium decays Generation

O-Ps -> 3γ p-Ps -> 3γ

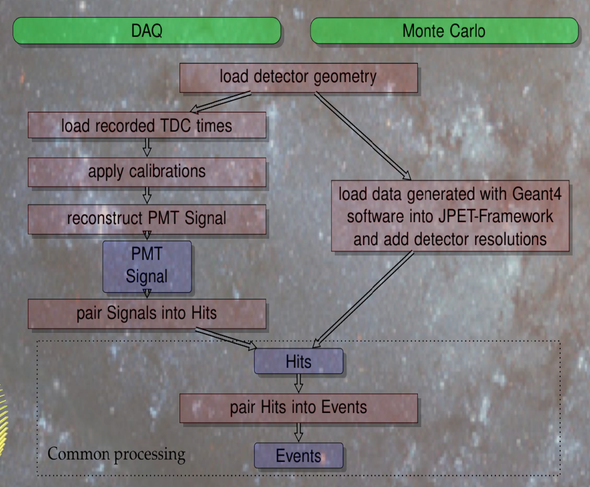


Positronium Lifetime



Ps Lifetime = $Time_{STOP} - Time_{START}$

Scope



Positronium atom decays

nγ (n=2,4,6,..)

S=0 ↓↑ - ↑↓ **Para**–positronium (**p - Ps**), **τ(vac)** = 0.125 ns, $^1S_0$

↑↑

↑↑ + ↓↓

↓↓

(2n+1)γ (n=3,5,..)

S=1 **ortho** – positronium (**o - Ps**), **τ(vac)** = 142ns, $^3S_1$

	$^1S_0$	$^3S_1$
L	0	0
S	0	1
C	+	-
L=0 -> P	-	-
CP	-	+

References

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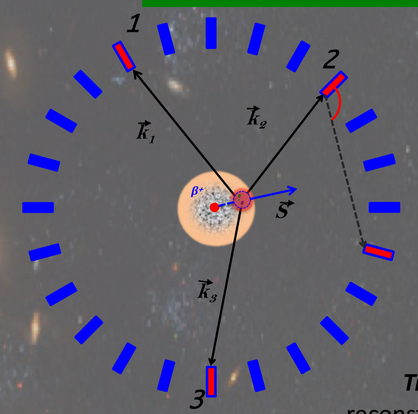
We acknowledge the support by the Foundation for Polish Science through the MPD and TEAM POIR.04.04.00-00-4204/17, the National Science Centre through the grant No. 2016/21/B/ST2/01222, 2017/25/N/NZ1/00861, the Ministry for Science and Higher Education through grants no. 6673/IA/SP/2016,7150/E- 338/SPUB/2017/1, 7150/E-338/M/2017, 7150/E- 338/M/2018 and 7150/E-338/M/2019.

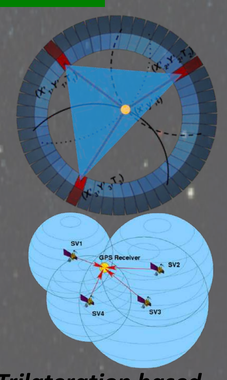
Tests on discrete symmetries in the decays of o-Ps into 3 γ

Operators (Symmetric - odd)	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1$	+	-	+	-	-
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	-	+	-
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	-	-	-	+
New operators available with J-PET				With	$\vec{\varepsilon}_i = k_i \times \vec{k'}_i$
$\vec{k}_2\cdot\vec{\varepsilon}_1$	+	-	-	-	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	-	+	-
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$	+	-	+	-	-

Discrete symmetries test operators for the o-Ps -> 3 γ process [16]. The odd-symmetric operators are marked with "-" and are available for studies at theJ-PET system

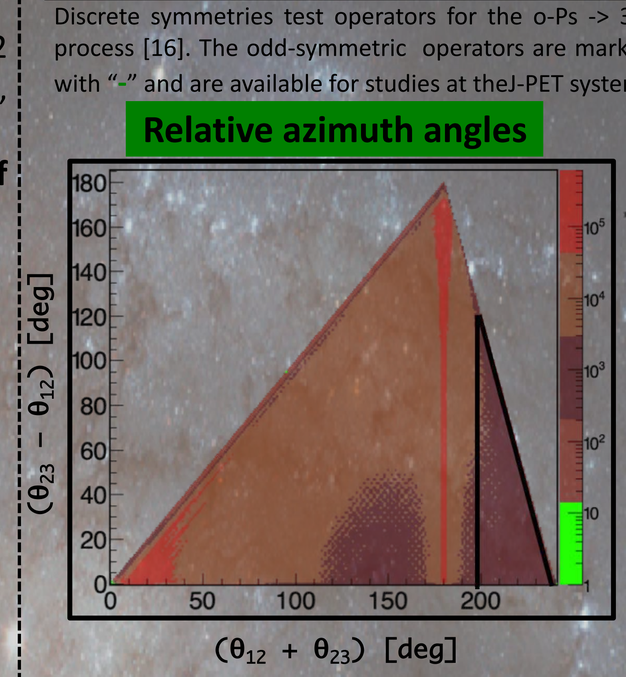
o-Ps Spin orientation



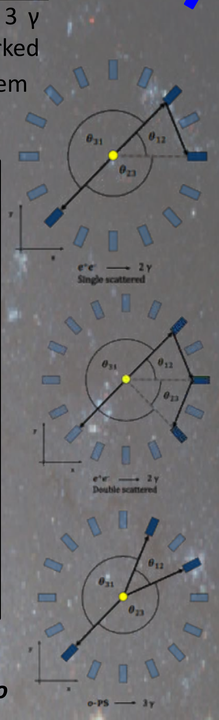


Trilateration based reconstruction of ***annihilation point*** in ***o-Ps -> 3γ*** decay [18]

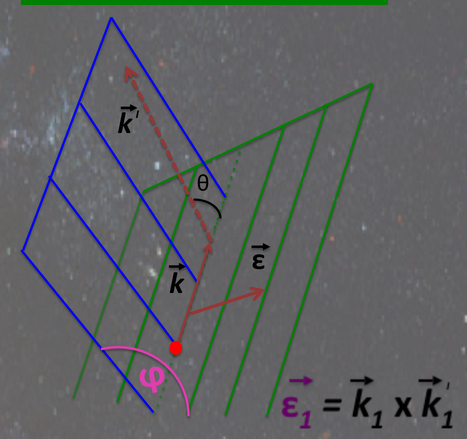
Relative azimuth angles



Distribution of events with 3 hits for ***sum of two smallest angles*** $\vartheta_{12} + \vartheta_{23}$ and their ***difference*** $\vartheta_{23} - \vartheta_{12}$, where each hit refers to the interaction of photon with individual scintillator



Photon's Polarization



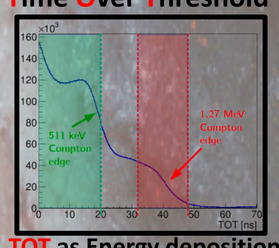
Determination of **photon's polarization** direction based on **Compton scattering** [17,20] which allow to construct additional odd-symmetric operators.

Charge conjugation symmetry

Selection of photons from different origin

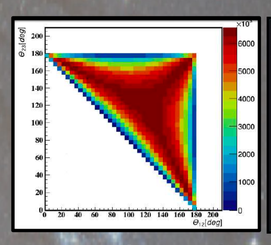
Time Over Threshold

o-Ps -> 3γ
Energy ≤ 511 keV
$^{22}Ne^*$
Energy = 1274.6 keV

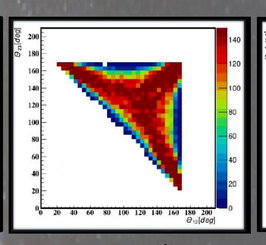


TOT as Energy deposition

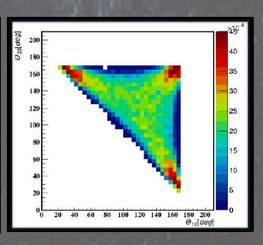
Monte Carlo Simulations (Geant4 based)



Generated events [19]

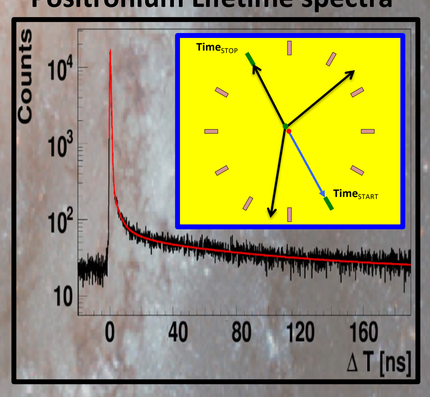


Reconstructed events

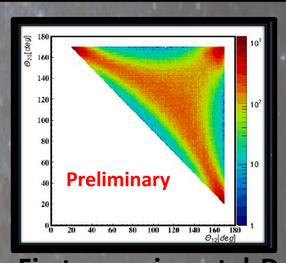


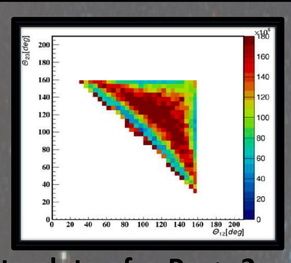
Efficiency map

Positronium Lifetime spectra



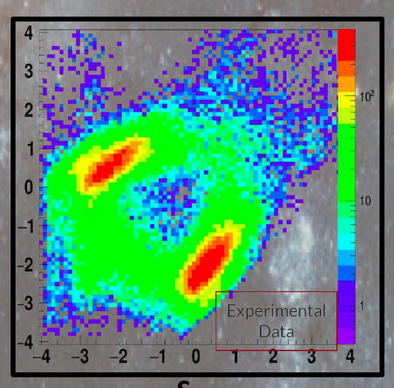
Experimental results using ^{22}Na source (1 MBq) surrounded by XAD4 matrial in center of small annihilation chamber



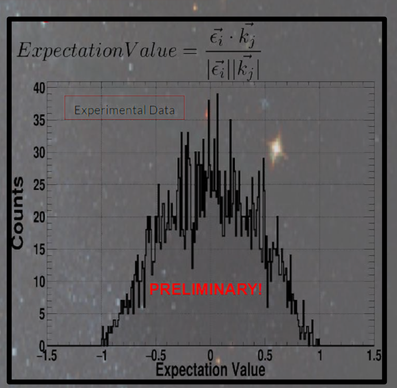


First experimental Dalitz plots of o-Ps -> 3γ.
Right figure is corrected with the efficiency map of detector estimated using the simulations.

Time reversal symmetry : $< \vec{\varepsilon} \cdot \vec{k} >$



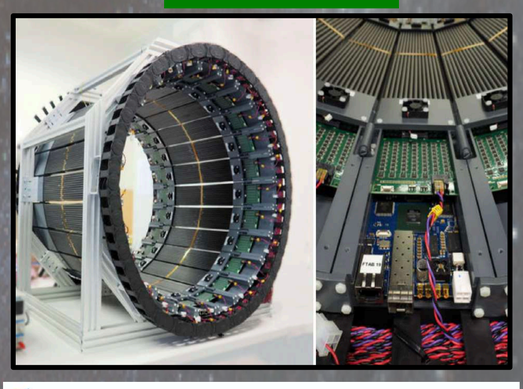
Assignment of the scatter photon to its primary based on the scatter test (S) : Diff. of the calculated and measured *time of flight of Scatt. photon*.



Measured $< \vec{\varepsilon} \cdot \vec{k} >$ = **3.2 x 10^{-4}** +/- 2.2 x 10^{-3}
(based on 1% of analysed data)
No T-Symmetry Violation is observed with a precision of ~10^{-3}

Future Perspectives :

Modular J-PET



- ❑ **J-PET detector** based on plastic scintillators is **constructed** and **commissioned**.
- ❑ The capability to measure **photon's polarization** direction will **allow to study** the phenomena like **multi-particle entanglement** [17, 20] and also adds up **more symmetric-odd operators**.
- ❑ Experimental results on T violation with the full measured data, ***we can improve the precision limit of time symmetry violation*** at least of an order of magnitude than the best measured value yet [4].
- ❑ **New** prototype **Modular/Portable J-PET** made of 24 modules where each module is composed of 13 scintillators will increase the detector acceptance.

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