# Studies of the discrete symmetries in the decays of positronium

## with **J**agiellonian **P**ositon **E**mission **T**omograph

J-PET

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ETC* STRANEX Workshop, Trento, October 2019

**Framework of J-PET Project**

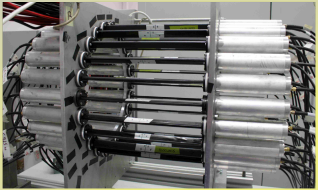
- Design and novel solutions
- Positronium atom

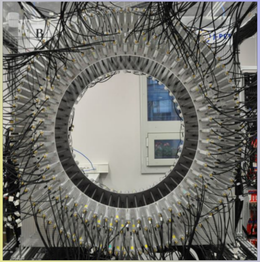
**Topics for and methods of investigation**

- **Discrete symmetries in physics**
- Medical diagnostics
- Mirror Matter
- Photon entanglement

J-PET Group in Frascati, September 2019

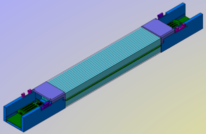
# J-PET detector - construction ideas (1)

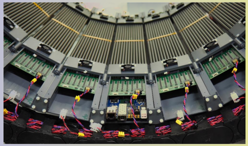


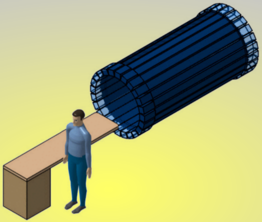


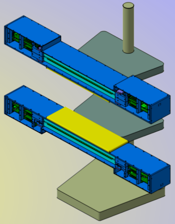
- Novel approach of using in Positon Emission Tomography plastic scintillators instead of crystal ones (cheaper, faster, longer elements - larger Field Of View)
- Great time resolution and lower pile-ups
- Good angular resolution and small light attenuation

# J-PET detector - construction ideas (2)





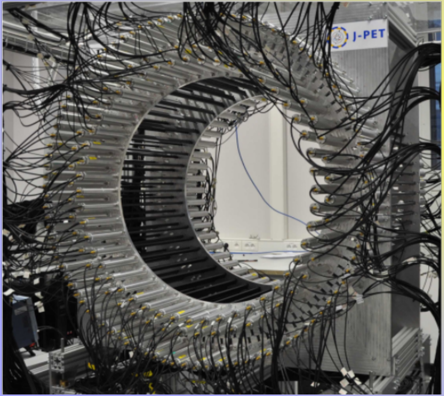


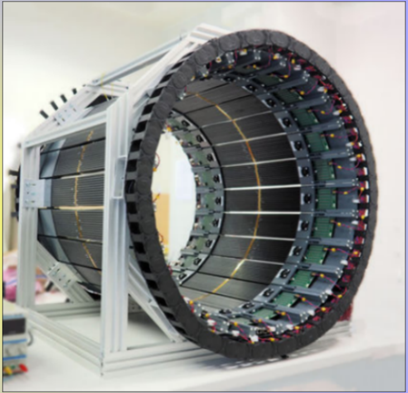


- Continuous data readout with trigger-less acquisition system
- Signals from Compton scattering instead of photoelectric effect (as traditionally in crystal-made tomographs)
- Flexibility of construction design thanks to modular approach (sizes, shapes, layers)

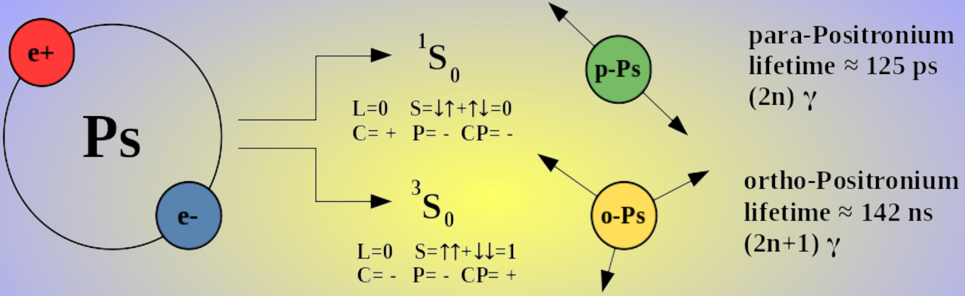
# J-PET detector - prototypes

Big Barrel
192 scintillators
384 vacuum tube PMs
probing on 4 thresholds



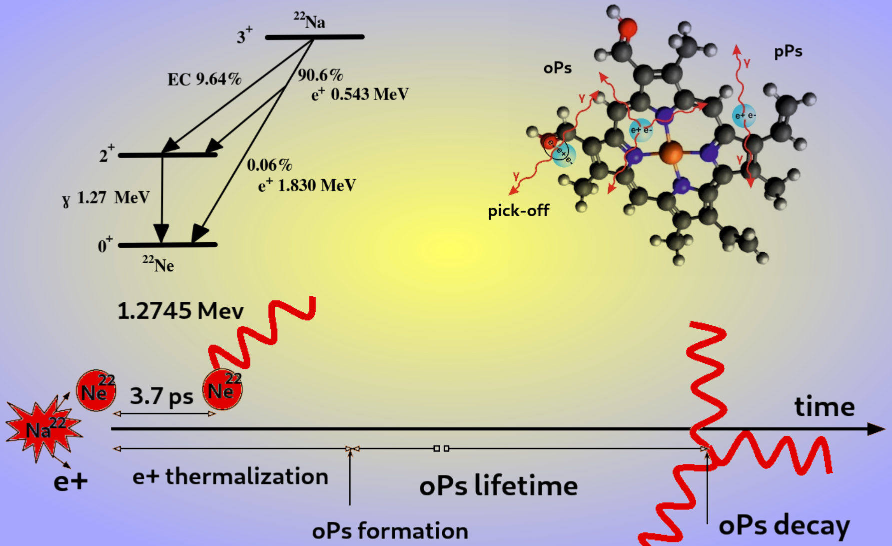



Modular Detector
24 modules x 13 scintillators
2496 SiPMs (8 per scintillator)
probing on 2 thresholds




- lightest purely leptonic object
- simultaneously an atom and an anti-atom
- bound by a central potential - P eigenstate
- symmetric under the exchange of particles into anti-particles - C eigenstate
- thus combined - eigenstate of the CP operator

# Positronium atom (2) - formation in a material



## Discrete symmetries in physics

- **Parity transformation**: $P(\vec{x}) = -\vec{x}$
  Not conserved by weak interactions (discovered in the $^{60}Co \rightarrow {}^{60}Ni\, e^{-} \bar{\nu}$ decay)
  [C. S. Wu et al., Phys. Rev. 105, (1957) 1413]
- **Time reversal transformation**: $T : t \rightarrow -t$
  Violated by weak interactions (neutral kaons, $B^0$ meson system) [A. Angelopoulos et al., Phys. Lett. B 444, (1998) 43; J. P. Lees et al.,Phys. Rev. Lett. 109, (2012) 211801]
- **Charge conjugation transformation**: C : particle $\rightarrow$ antiparticle
  $C|\gamma > -1|\gamma >$
  Violation by weak interactions discovered in $\pi^{+}\mu^{+}\nu_{\mu} \rightarrow \nu_{\mu}\nu_{e}\bar{\nu}_{\mu}e^{+}$
  [R. L. Garwin et al., Phys. Rev. 105, (1957) 1415]
- **CP symmetry** - relevant in explanation of matter-antimatter imbalance
  Violated in weak processes (kaons, $B^0$)
  [J. H. Christenson et al.., Phys. Rev. Lett. 13, (1964) 138]
  [B. Aubert et al., Phys. Rev. Lett. 87, (2001) 091801]
- **CPT Theorem** - always conserved in any local quantum field theory

- **Searching for forbidden decays of para- and ortho-Positronium**

  $\mathrm{BR}(\text{p-Ps} \to 3\gamma/\text{p-Ps} \to 2\gamma) < 2.8 \times 10^{-6}$ at 68% C.L.
  [A.P. Mills, S. Berko, Phys. Rev. Lett. 18, 420 (1967)]

  $\mathrm{BR}(\text{p-Ps} \to 5\gamma/\text{p-Ps} \to 2\gamma) < 2.7 \times 10^{-7}$ at 90% C.L.
  [P.A. Vetter, S.J. Freedman, Phys. Rev. A66, 052505 (2002)]

  $\mathrm{BR}(\text{o-Ps} \to 4\gamma/\text{o-Ps} \to 3\gamma) < 2.6 \times 10^{-6}$ at 90% C.L.
  [J. Yang et al., Phys. Rev. A54, 1952 (1996)]

- **Estimations of reachable limits in J-PET (by S. Bass [arxiv 1902.01355v1])**
  – 10 MBq positronium source
  – 4 layer detector geometry
  – 365 days of data taking

  - $9.4 \times 10^{10}$ 3 photon oPs
  - $3 \times 10^{11}$ 2 photon pPs

# P, T, CP, CPT investigation with odd operators

- Measurement of the **expectation value of the symmetry-odd operators**

- $\vec{S}$ - oPs spin vector
- $\vec{k}_i$ photon momentum vector
- $\vec{\epsilon}_i$ photon polarization vector
  $\vec{\epsilon}_i = \vec{k}_i \times \vec{k'}_i$

There are results only for cases of:

- CPT

$\langle \vec{S} \cdot (\vec{k}_1 \times \vec{k}_2) \rangle = 0.0026 \pm 0.0031$

[P.A. Vetter, S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003)]

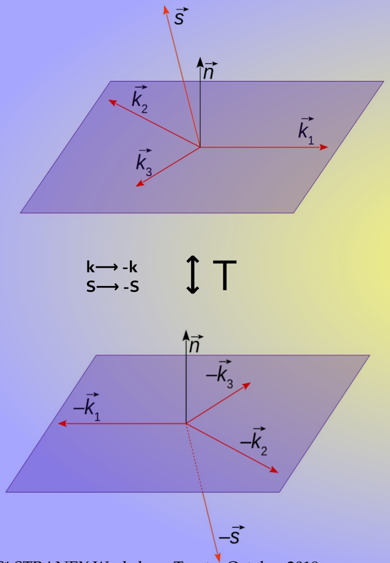
- CP

$\langle (\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)) \rangle = 0.0013 \pm 0.0022$

[T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401]

| operator | C | P | T | CP | CPT |
|---|---|---|---|---|---|
| $\vec{S} \cdot \vec{k}_1$ | + | - | + | - | - |
| $\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$ | + | + | - | + | - |
| $(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$ | + | - | - | - | + |
| $\vec{k}_1 \cdot \vec{\epsilon}_2$ | + | - | - | - | + |
| $\vec{S} \cdot \vec{\epsilon}_1$ | + | + | - | + | - |
| $\vec{S} \cdot (\vec{k}_2 \times \vec{\epsilon}_1)$ | + | - | + | - | - |

# T example

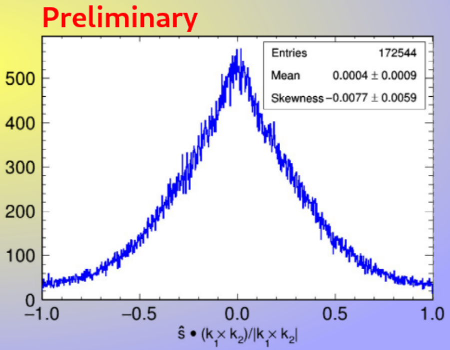



- $\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$

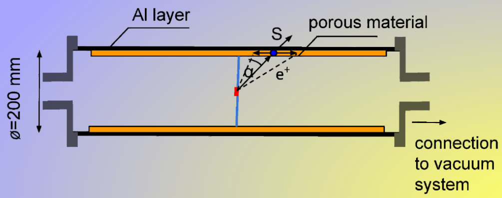
$\rightarrow \alpha : \angle(\vec{S}, \vec{k}_1 \times \vec{k}_2)$

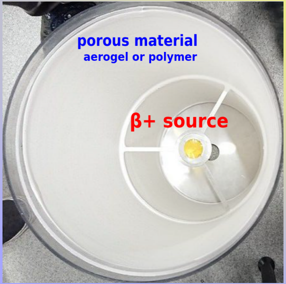
$\rightarrow N(\alpha) \neq N(\alpha + 180)$

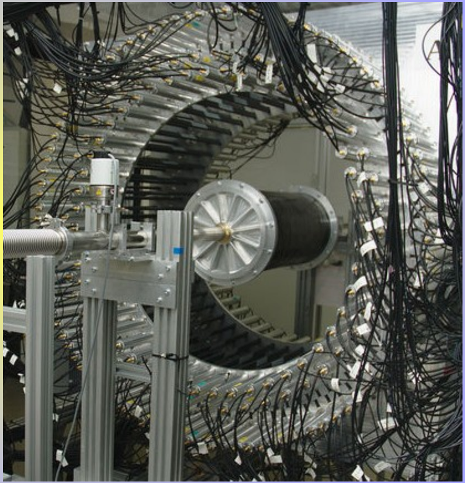
$\rightarrow$ symmetry breaking



# Investigation methods (1) - oPs "factory"

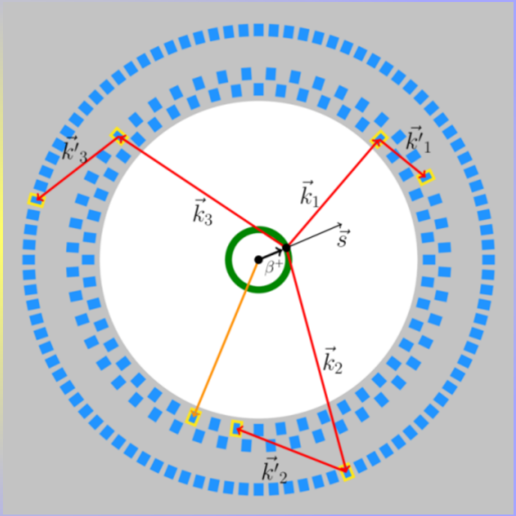


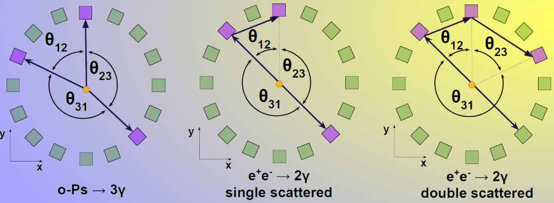
# Investigation methods (2) - signal signature

- register 3 primary photons
- large lifetime (deexcitation - annihilation time difference)
- reconstruct decay vertex with GPS-like method (Time-of-Flight constraint)
- determine spin of oPs based positron longitudinal polarization
- determine polarization using secondary photon from Compton scattering

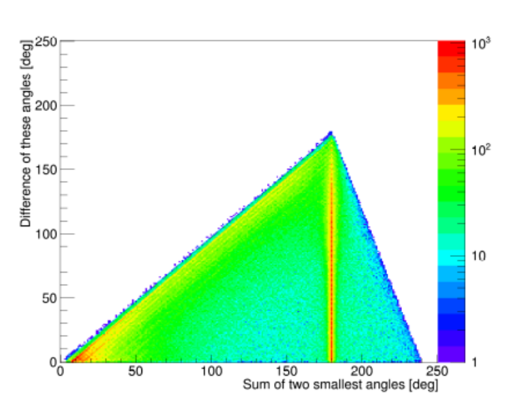


▶ Selecting oPs candidates by looking at relative angles between 3 photon interactions:

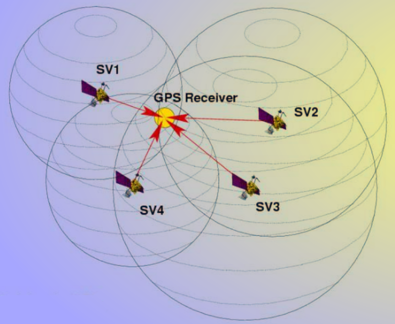
$$\theta_{1-2} < \theta_{2-3} < \theta_{3-1}$$
$$\theta_x = (\theta_{1-2} + \theta_{2-3}), \quad \theta_y = (\theta_{2-3} + \theta_{1-2})$$

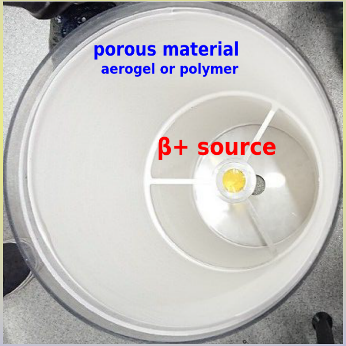


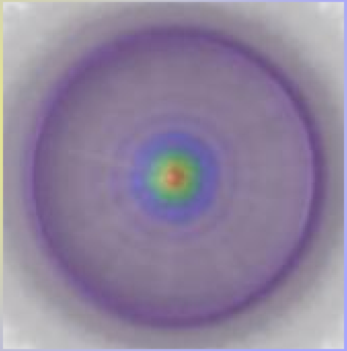

$\theta_x > 180$ $\quad\theta_x \approx 180$ $\quad\theta_x < 180$



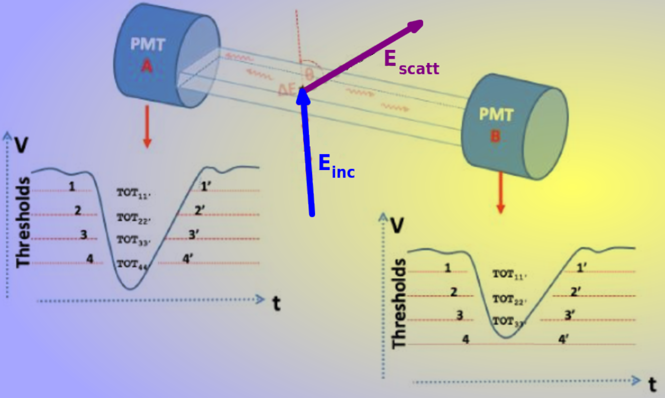
- Reconstruction is based on a trilateration-based method - finding cross-section of three spheres (or circles in the plane of 3 vectors) based on a photon interaction position and Time-of-Flight.



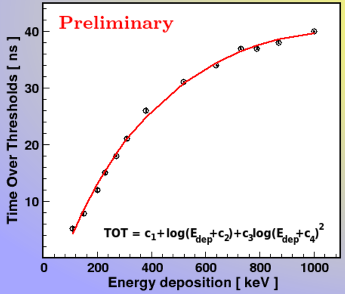
# Investigation methods (5) - energy measure

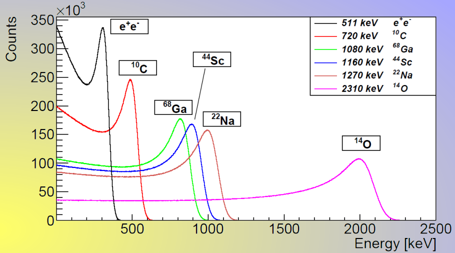


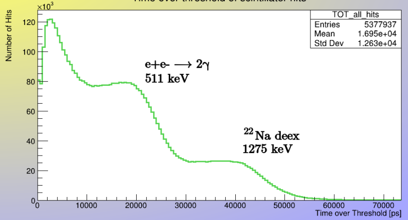

$$TOT = \sum_{PM_A,PM_B} \sum_{THR1,4} t_{diff}^{PM,THR}$$

Energy deposition in Compton scattering:

$$E_{dep} = E_{inc}\left[1 - \frac{1}{1+\frac{E_{inc}}{E_{e-}}(1-\cos\theta)}\right]$$



# Summary and outlook

Summary

- Jagiellonian Positon Emission Tomograph is an multipurpose experiment for applications in medical diagnostics and low-energy particle physics
- technical solutions used in J-PET provide interesting flexibility of usage while maintaining low cost of construction
- wide range of measurement techniques provide with various possibilities of investigations in fundamental symmetries tests in the leptonic sector

Current prospects of J-PET

- starting measurements with modular detector prototype - higher acceptance
- extending pool of computing resources

Thank you for your attention