Testing CPT symmetry in ortho-positronium decays with the J-PET facility

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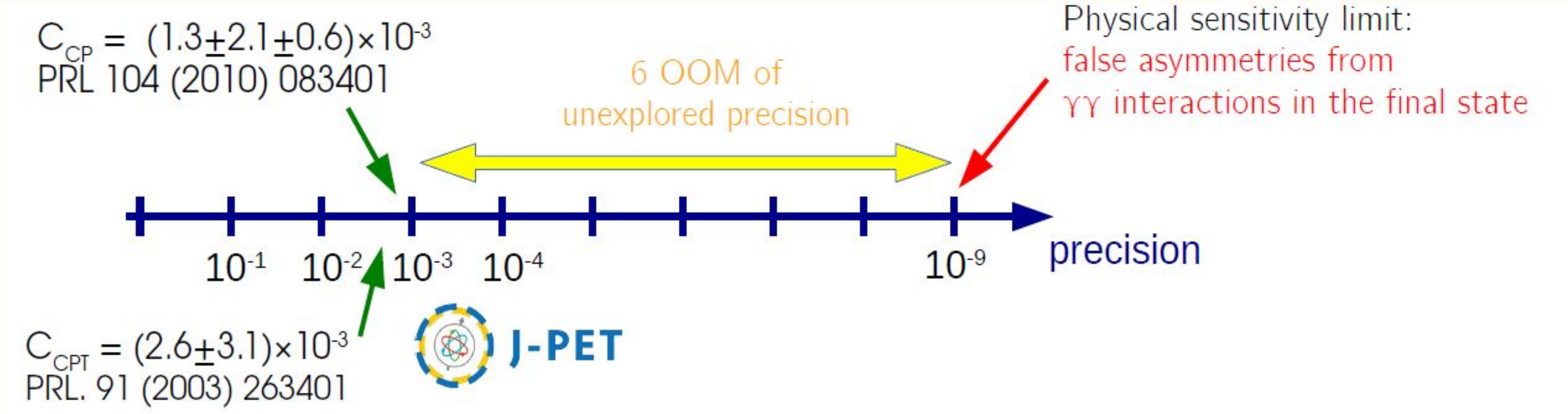
on behalf of the **J-PET** collaboration

Symposium: Fundamental Physics
with exotic atoms and radiation detectors
Frascati, 25-26.11.2021

Motivation: discrete symmetry tests with o-Ps decays

- Discrete symmetries are scarcely tested with leptonic systems
  - Neutrino oscillations: Dirac phase, δCP ~3σ level [T2K, *Nature 580 (2020) 339*]
  - Electron EDM < 1.1×10^{-29} [ACME, *Nature 562 (2018) 355*]
- Violation of CP and T symmetries have been observed only for systems including quarks, never discovered in any processes involving purely leptonic matter
- So far performed experiments with Ps atoms excluded violation of discrete symmetries as CP, T or CPT only at the level of about 0.3% - many orders of magnitude less precise than the accuracies achieved in the quark sector
  Ps is the only system consisting of charged leptons used for tests of CP and CPT to date



- symmetries tests can be made with a very high precision limited, only by the effects due to the weak interaction: 10^{-14} and photon-photon interaction: 10^{-9}. (Standard Model Calculations)

[Phys. Rev. A 37, 3189 (1988), Z. Phys. C 41, 143 (1988), M. S Sozzi "Discreet Symmetries and CP violation"]

Motivation: discrete symmetry tests with o-Ps decays

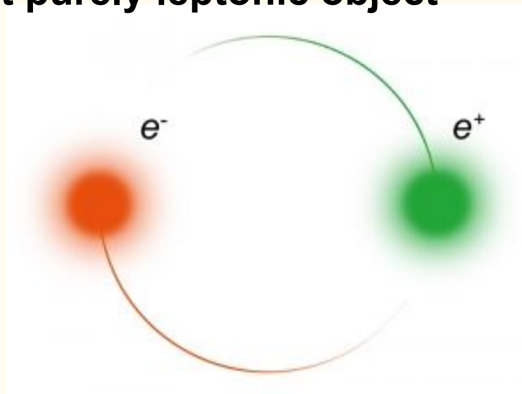
➢ **POSITRONIUM - the lightest purely leptonic object**

bound by a central potential

$\Downarrow$

<u>is eigenstate of the parity operator P</u>

$$P|Ps>=(-1)^L|Ps>$$



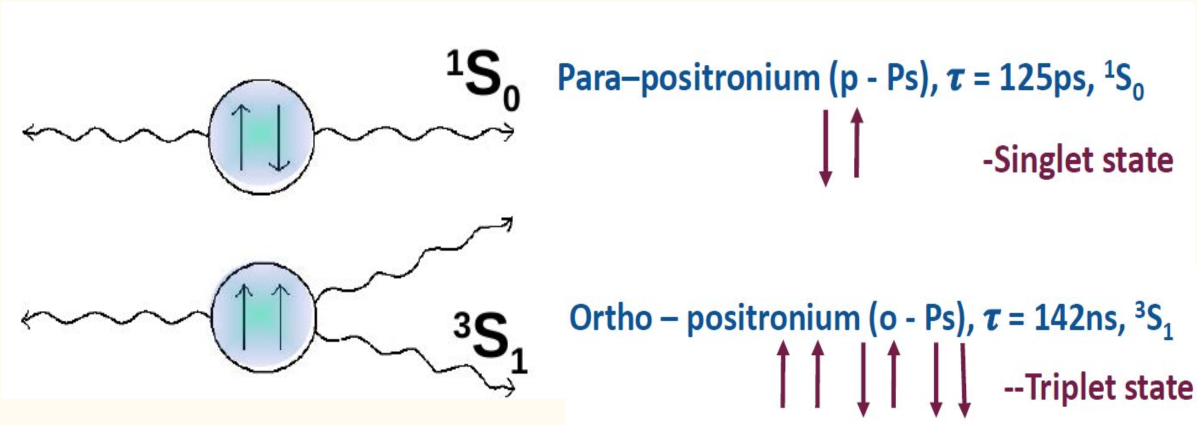
symmetric under the exchange of particles - anti-particles

$\Downarrow$

<u>is eigenstate of the charge conjugation operator C</u>

$$C|Ps>=(-1)^{L+S}|Ps>$$

<u>eigenstate of the CP operator</u>



even number of photons

symm. of charge conjugation C

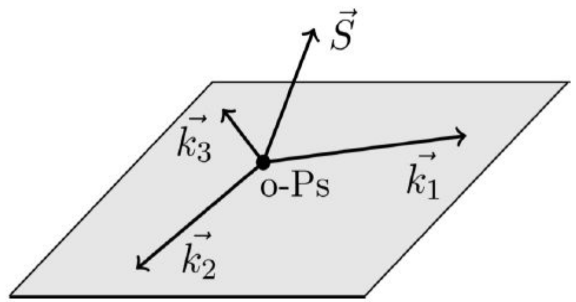
odd number of photons

Ps state	τ [ns]	L	S	J	J_z	P	C	CP
$^1S_0$ (para-Ps)	0.125	0	0	0	0	-	+	-
$^3S_1$(ortho-Ps)	142	0	1	1	-1,0,1	-	-	+

Testing discrete symmetries with angular correlations in o-Ps→3γ decays

Measurement the expectation value of the symmetry odd-operators

$$e^+e^- \rightarrow \text{o-Ps} \rightarrow 3\gamma$$



$$\langle \hat{O} \rangle \stackrel{?}{=} 0 \quad \text{for an odd operator}$$

$$\Leftrightarrow \mathcal{CPT}(\hat{O}) = -1$$

$$\Leftrightarrow \mathcal{T}(\hat{O}) = -1$$

$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$

Required:

- the o-Ps spin determination
- of o-Ps→3γ decays selection

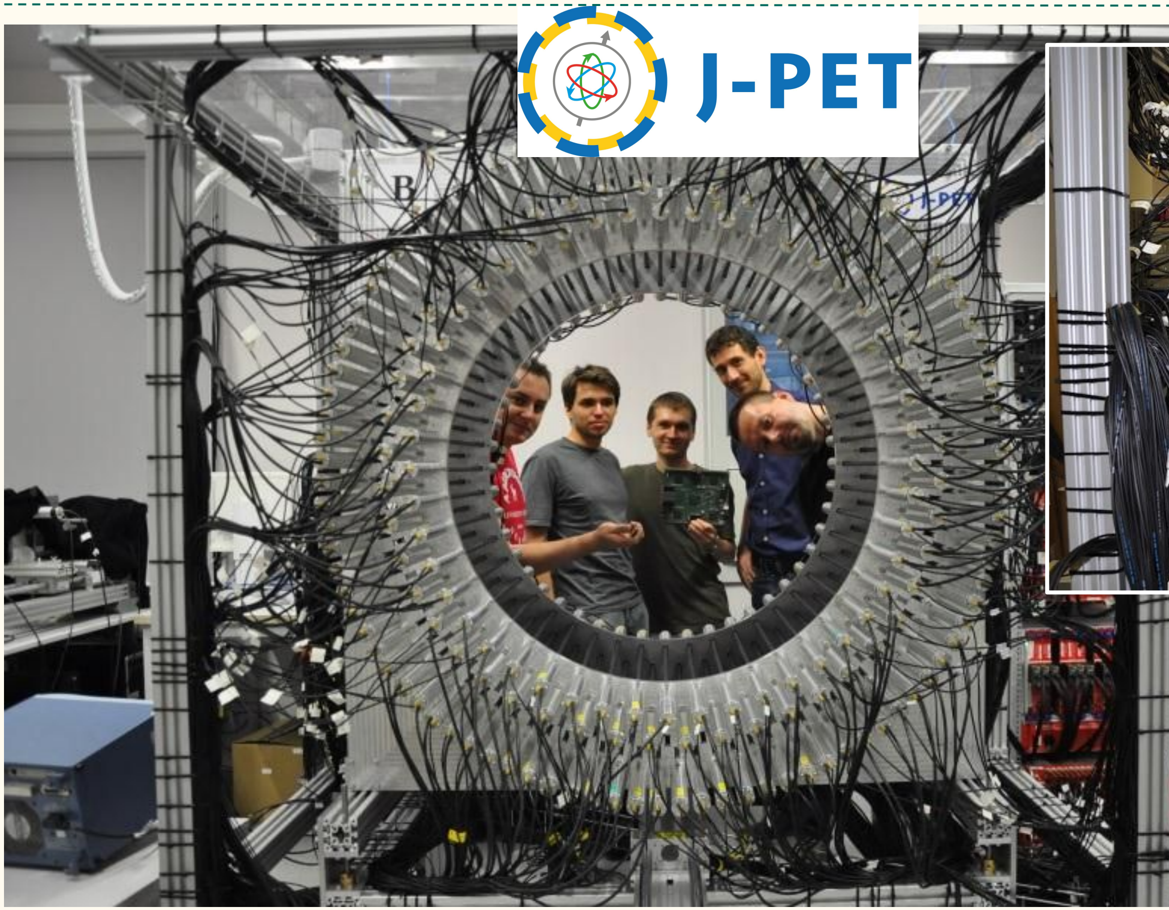
(determination of photons momenta)

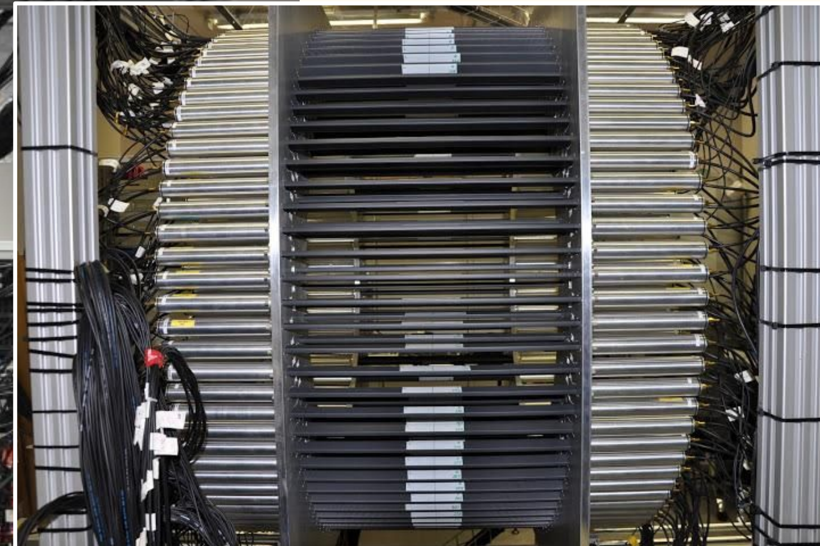
$$O_{CPT} = \hat{S} \cdot (\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2| = \cos\phi$$

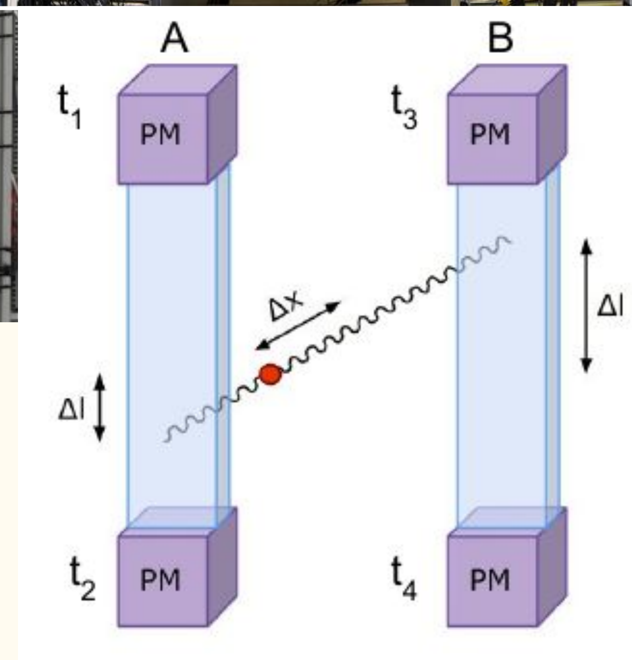
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\boxed{\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)}$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+
$\vec{k}_1 \cdot \vec{\varepsilon}_2$	+	-	-	-	+
$\vec{S} \cdot \vec{\varepsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2 \times \vec{\varepsilon}_1)$	+	-	+	-	-

[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509]

J-PET detector at Jagiellonian University in Kraków, Poland



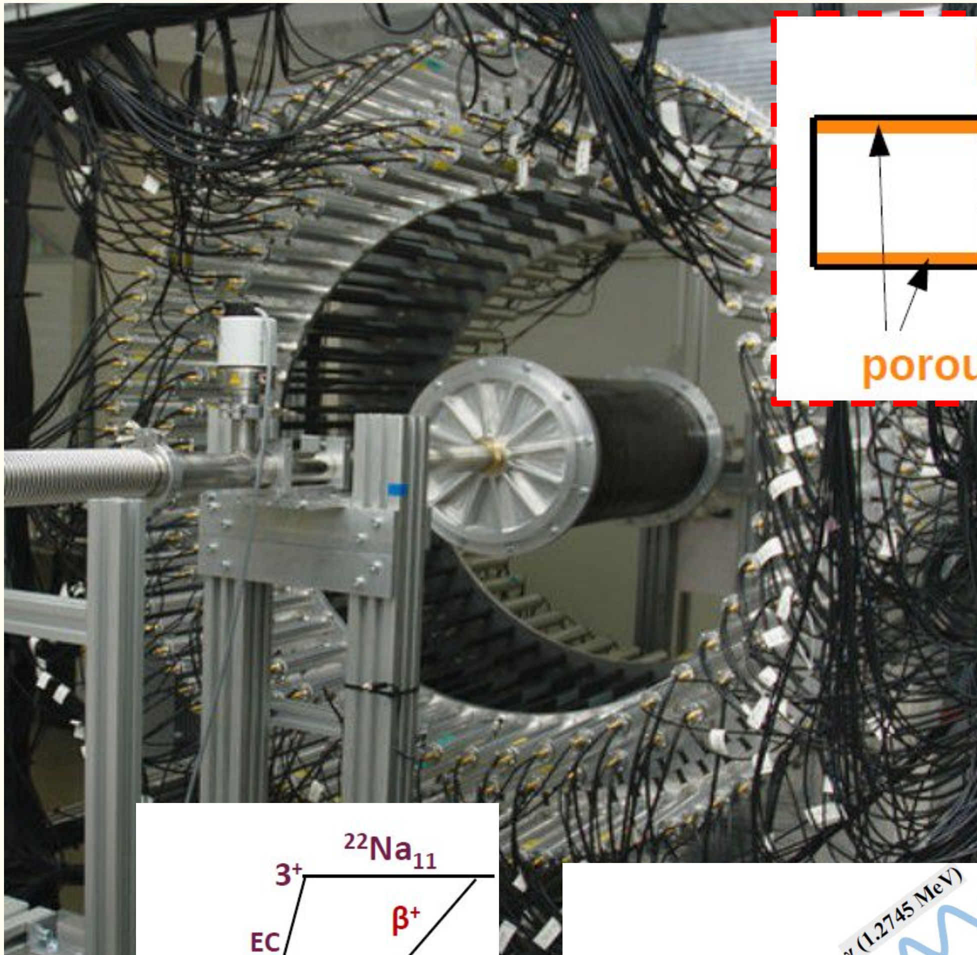


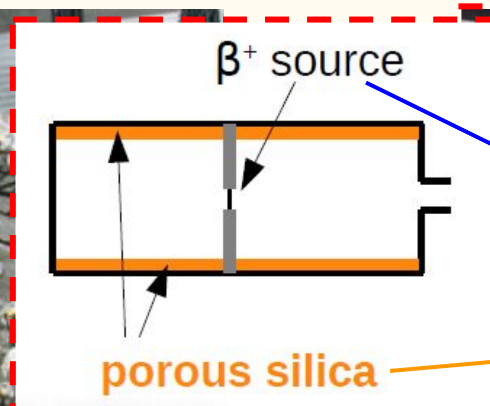


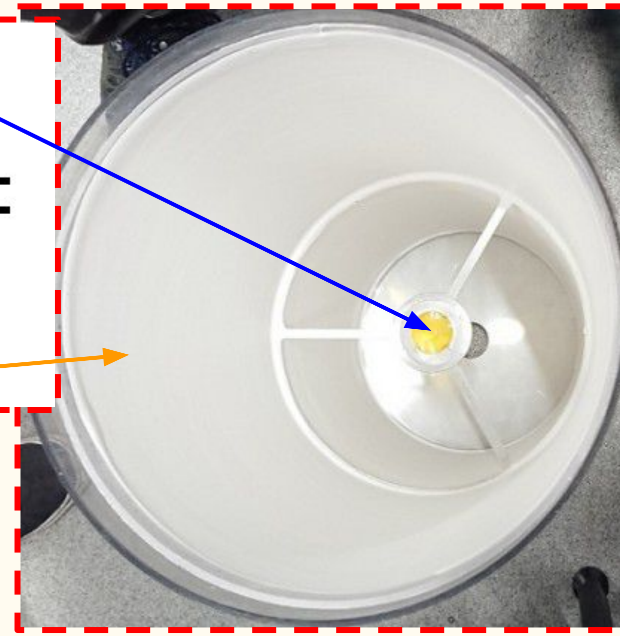
- 3 layers
- 192 EJ-230 scintillators: 7x19x500 mm^3
- 85 cm radius
- 384 R9800 photomultipliers,1536 channels
- multithreshold digital electronics and and the novel trigger-less DAQ

[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509; G. Korcyl, et al., IEEE Trans. Med. Imag. 37, 2526 (2018)]

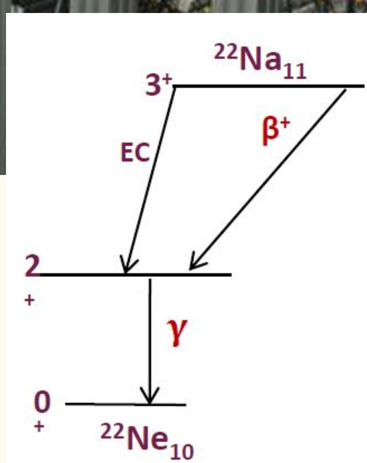
o-Ps production in J-PET with an annihilation chamber

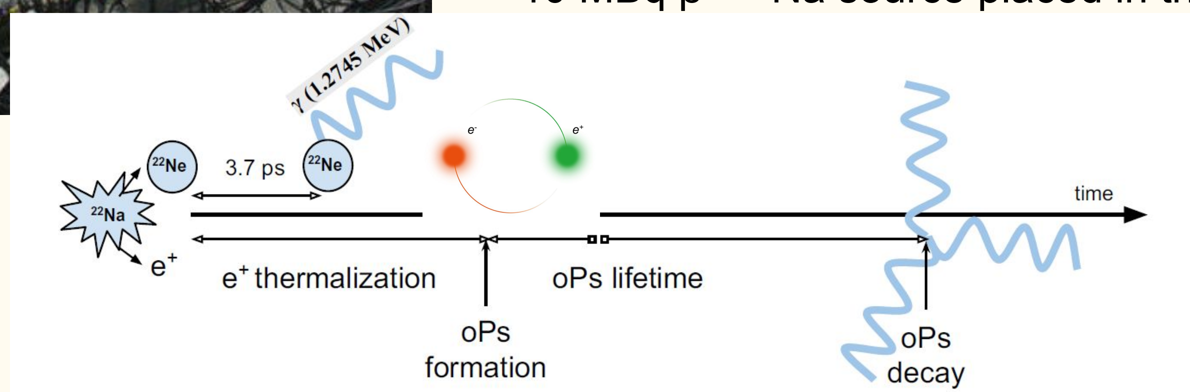






- Extensive-size chamber, R=12 cm
- Walls coated with porous silica material (o-P target)
- 10 MBq β+ ^{22}Na source placed in the center





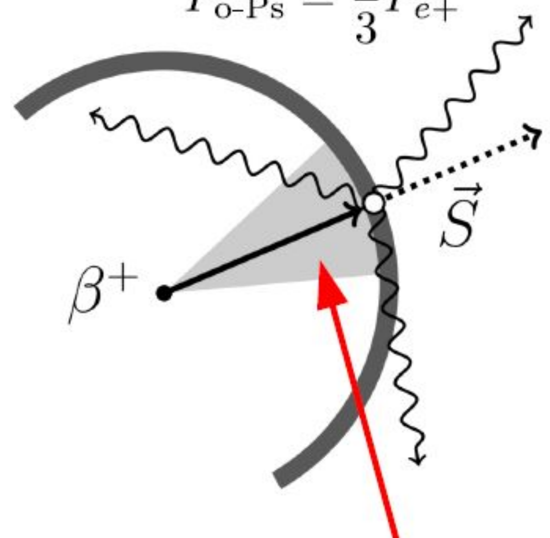
[D. Kaminska, et a.l., Eur. Phys. J. C (2016) 76:445]

o-Ps spin determination and o-Ps→3γ decays reconstruction in J-PET

o-Ps spin estimation:

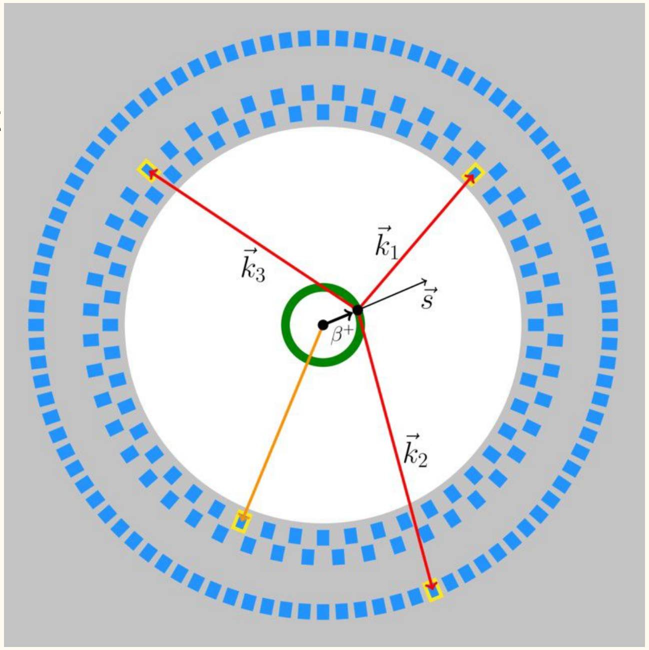
✶ e^+ spin estimated event-by-event recording multiple geometrical configurations
✶ effective polarization depends on o-Ps→3γ vertex resolution

$$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$$



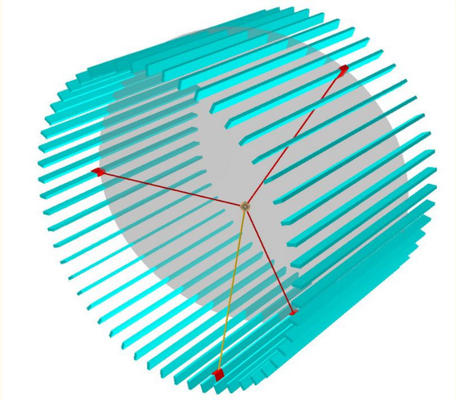
$$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$$

$$\mathrm{P}_{e+} = (N^{e+}_{+1/2} - N^{e+}_{-1/2}) \,/\, (N^{e+}_{+1/2} + N^{e+}_{-1/2})$$

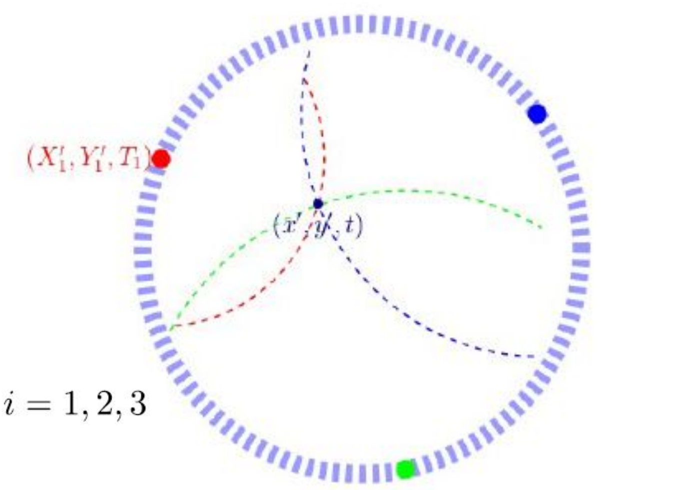


o-Ps→3γ decays reconstruction:

✶ Trilateration-based reconstruction to determine the o-Ps annihilation point



⇓



The decay point **(x',y')** in the decay plane and time **t** is an intersection of 3 circles, each corresponding to a possible origin points of the incident γ

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

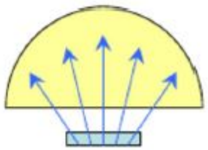
M. Mohammed, et al., Acta Phys. Pol. A 132, 1486 (2017)]

[A. Gajos et al., NIM A 819 (2016), 54-59]

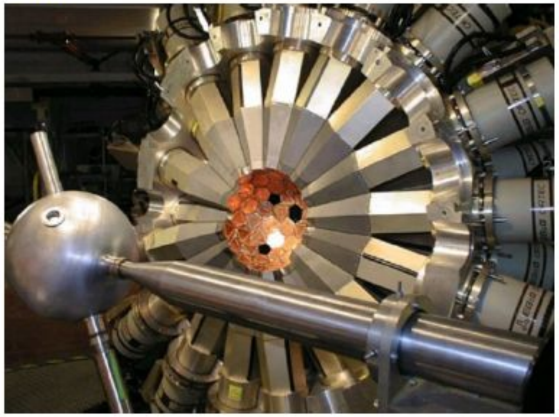
Gammasphere
PRL. 91 (2003) 263401

$C_{CPT} = (2.6\pm3.1)\times10^{-3}$

$$\vec{S}\cdot(\vec{k_1}\times\vec{k_2})$$



$$P_{e+} = \frac{v}{c}\cdot 0.686$$

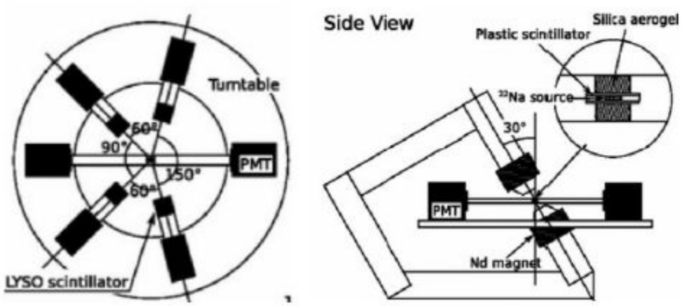


Limiting positron emission direction
1 Mbq β^+ emitter activity
4π detector but low angular resolution

Yamazaki et al.
PRL 104 (2010) 083401

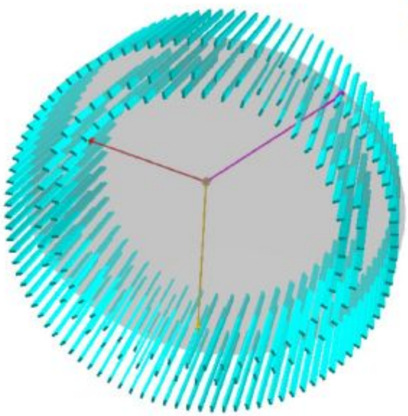
$$(\vec{S}\cdot\vec{k_1})(\vec{S}\cdot(\vec{k_1}\times\vec{k_2}))$$

$C_{CP} = (1.3\pm2.1\pm0.6)\times10^{-3}$



Polarized o-Ps using external B field
Inclusive measurement
Only certain angular configurations

J-PET



Recording multiple geometrical configurations

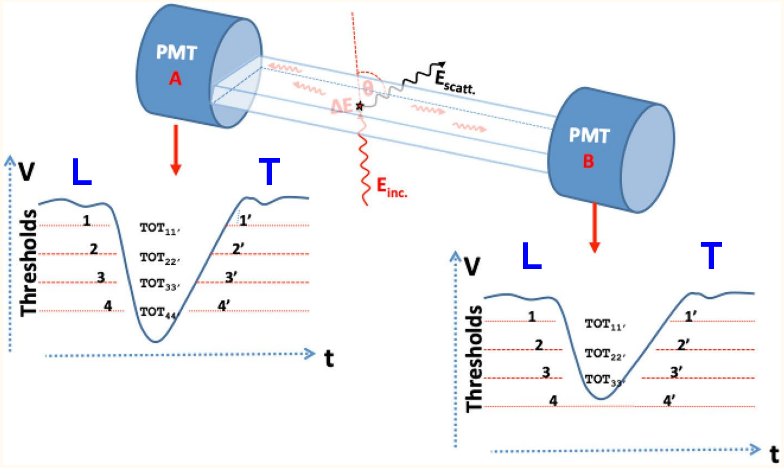
e+ spin estimated event-by-event

$$P_{e+} \approx \frac{v}{c}\cdot 0.91$$

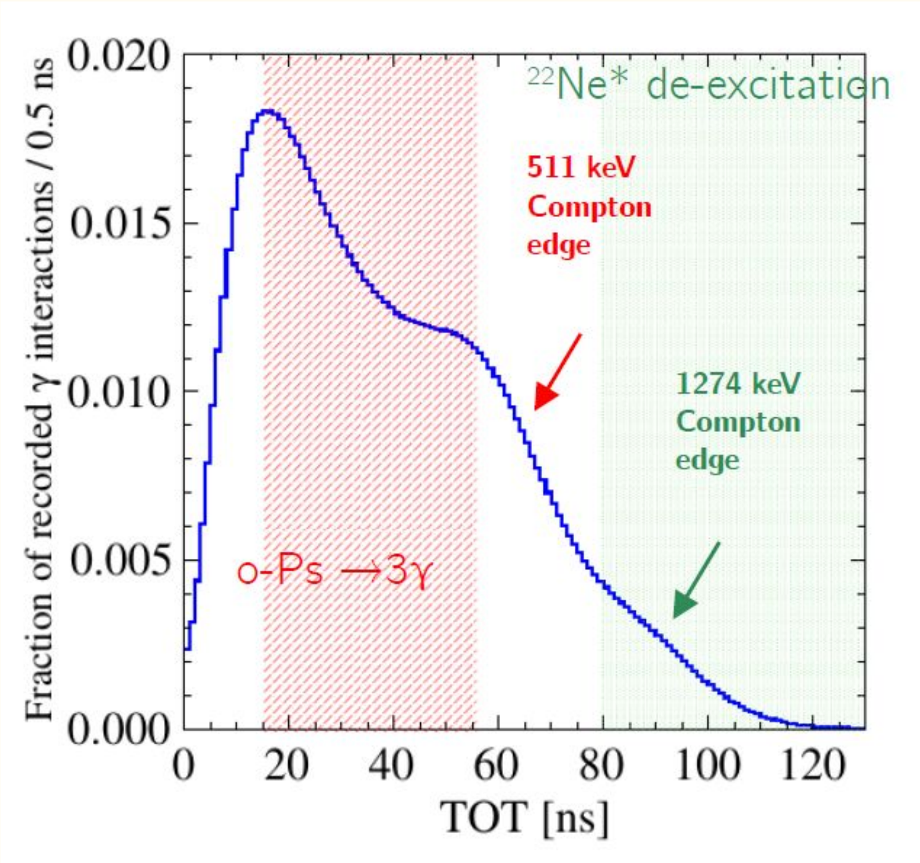
- Plastic scintillators = fast timing
  $\rightarrow$ using high β^+ emitter activity
  (tested up to 10 Mbq)
- Recording all 3 annihilation photons
- Angular resolution at 1° level

Courtesy of A. Gajos

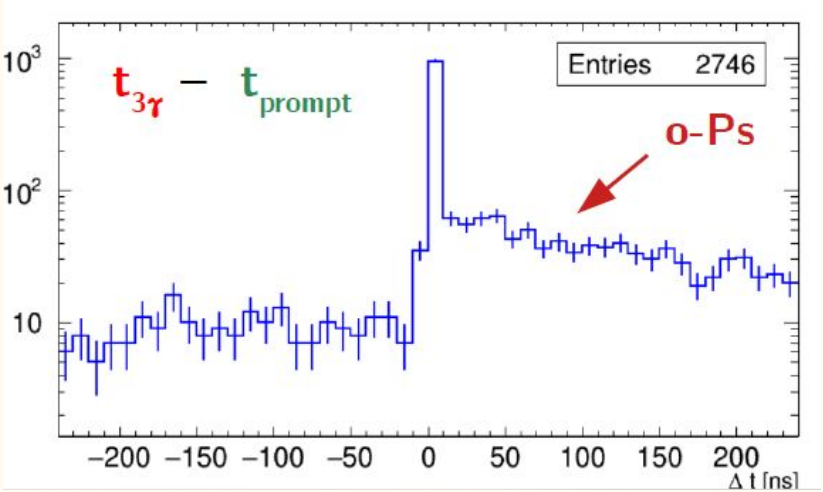
Identification of o-Ps→3γ annihilation events in J-PET



[S. Sharma, eta al., EJNMMI Phys. 7, 39 (2020)]



Using total Time Over Threshold (TOT) of PMT signals from a scintillator strip which corresponds to ɣ deposited energy



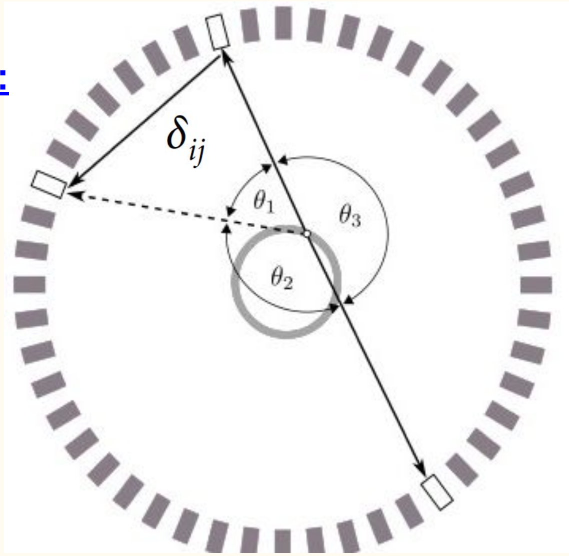
⇐ o-Ps presence in positron lifetime distribution

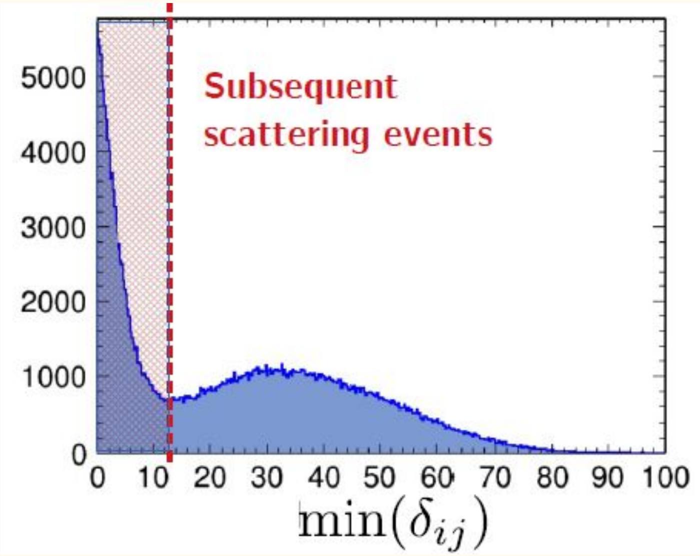
Background subtraction

Secondary Compton scatterings:

$$\star\ \delta_{ij} = |d_{ij} - c\Delta t_{ij}|$$

computed for each pair of annihilation photon candidates i and j (i,j=1,2,3)

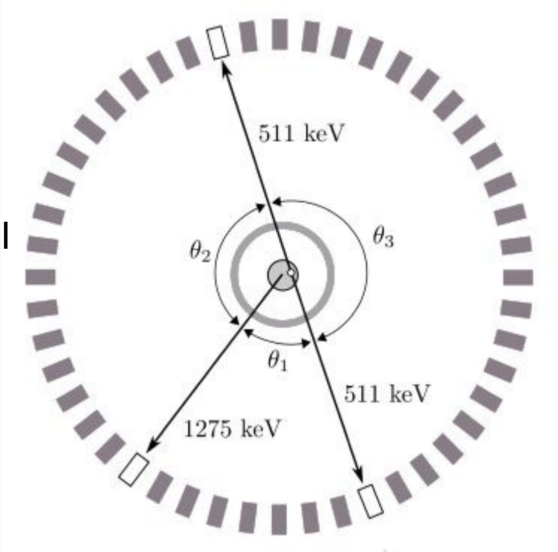


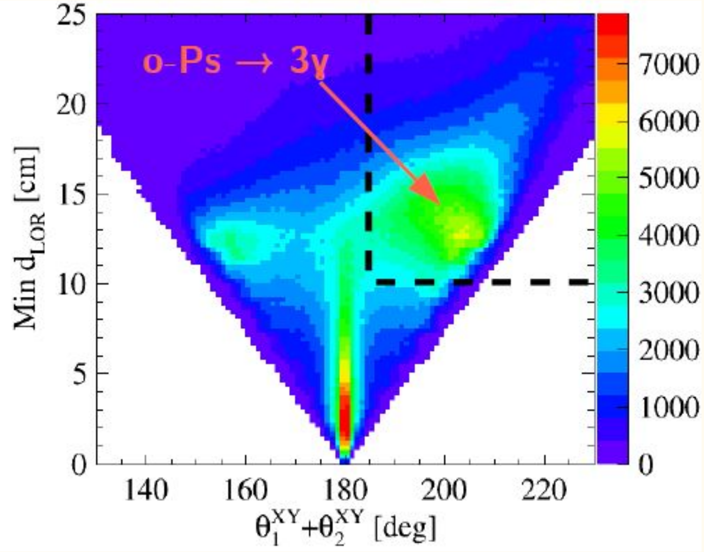


2γ from the β+ source setup coincident with de-excitation photon:

✶ distance between the β+ source location and the closest hypothetical 2γ annihilation point on a LOR between two recorded photon interactions

✶ the sum of the two smallest angles between azimuthal coordinates of the recorded γ interaction points



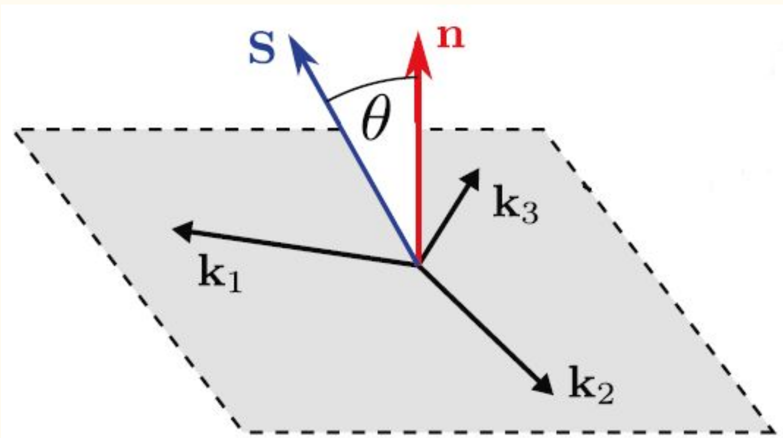


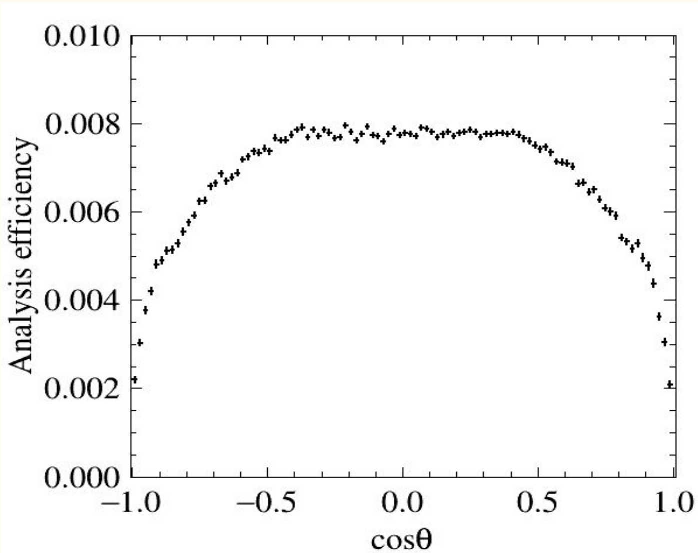
Determination of the CPT - asymmetric observable

$$O_{CPT} = \hat{S} \cdot (\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2| = \cos\phi$$

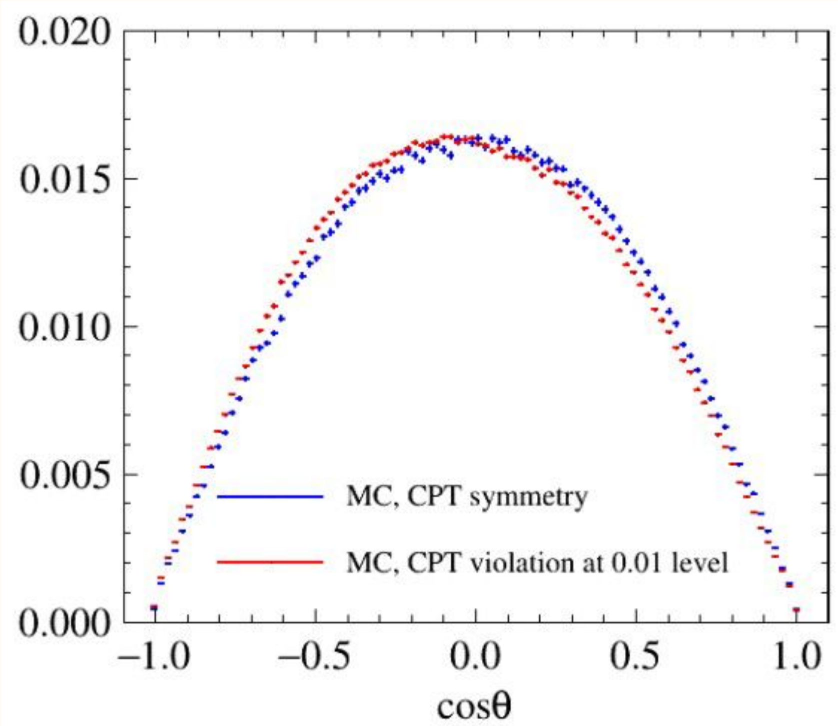
the angle between the direction of initial spin of the o-Ps atom and the normal to the decay plane

J-PET is sensitive to the full range of this operator





MC simulations



⇑

expected asymmetry in case of CPT violation

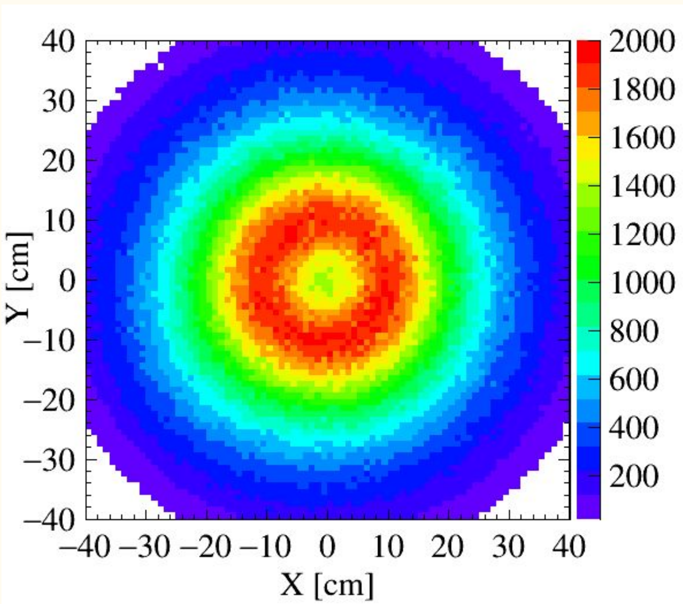
⇐ efficiencies evaluated with MC are symmetric in cosθ

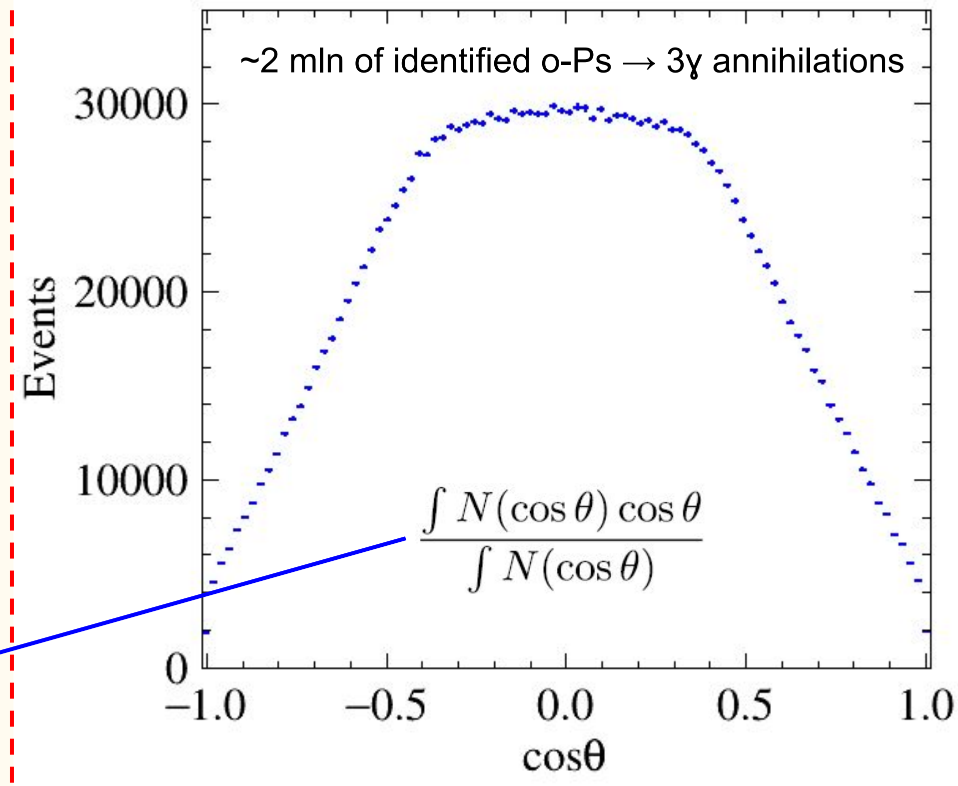
Determination of the CPT - asymmetric observable

$$O_{CPT} = \hat{S}\cdot(\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2| = \cos\phi$$

the angle between the direction of initial spin of the o-Ps atom and the normal to the decay plane

3ɣ image of the o-Ps production chamber in the tranverse view of the detector (the first!)





$$<O_{CPT}> = 0.00025 \pm 0.00036$$

P. Moskal, et al., Nature Commun. 12, 5658 (2021)

$$C_{CPT} = <O_{CPT}>/P = 0.00067 \pm 0.00095$$

the level of observed CPT violation (after correction of analyzing power)

stat error : 3.3×10^{-4}
syst error: 1.4×10^{-4}

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-021-25905-9 OPEN

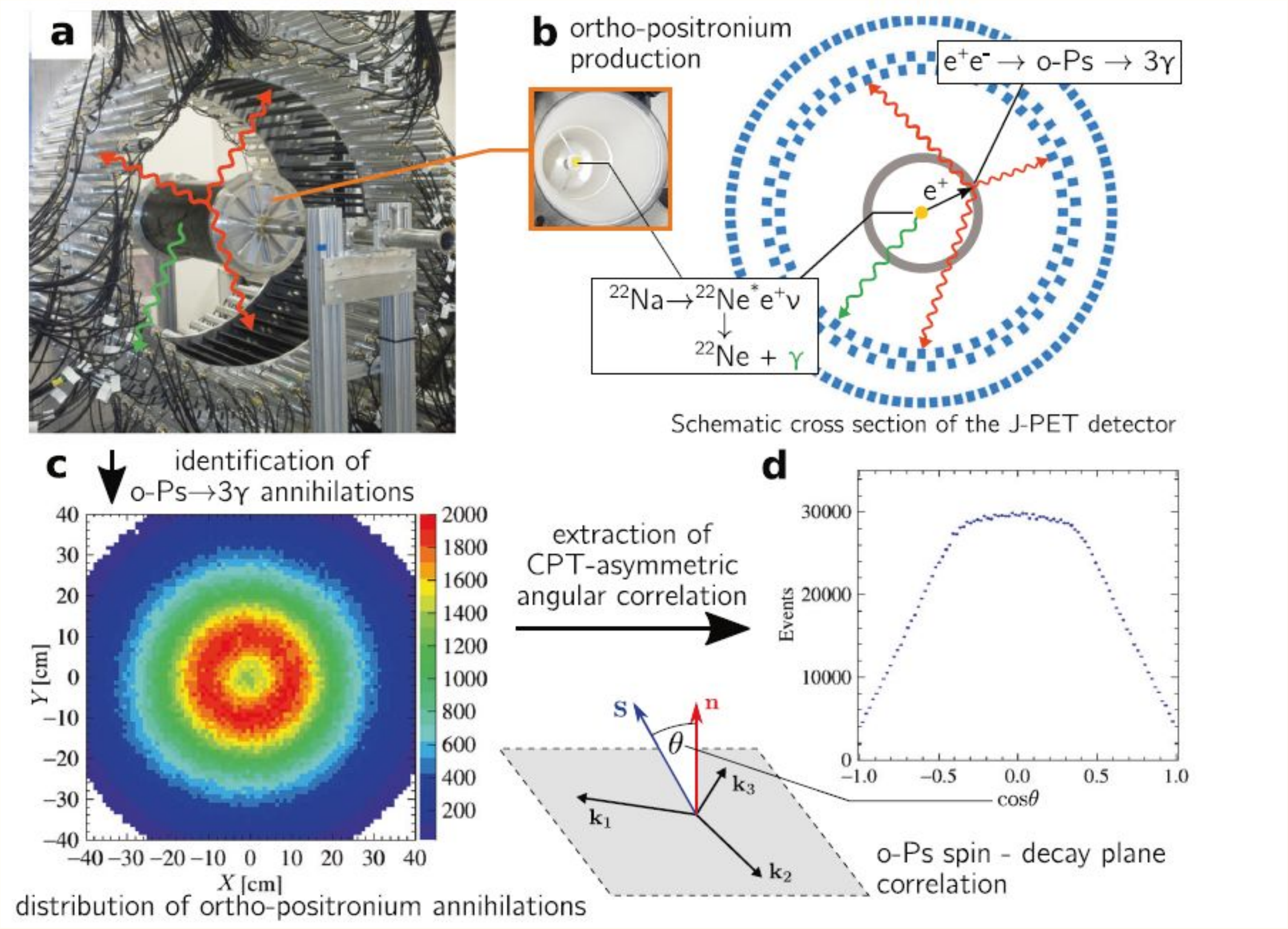
Check for updates

Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography

P. Moskal[1,2]✉, A. Gajos[1,2]✉, M. Mohammed[1], J. Chhokar[1,2], N. Chug[1,2], C. Curceanu[3], E. Czerwiński[1,2], M. Dadgar[1,2], K. Dulski[1,2], M. Gorgol[4], J. Goworek[5], B. C. Hiesmayr[6], B. Jasińska[4], K. Kacprzak[1], Ł. Kapłon[1,2], H. Karimi[1,2], D. Kisielewska[1], K. Klimaszewski[7], G. Korcyl[1,2], P. Kowalski[7], N. Krawczyk[1,2], W. Krzemień[8], T. Kozik[1], E. Kubicz[1,2], S. Niedźwiecki[1,2], S. Parzych[1,2], M. Pawlik-Niedźwiecka[1,2], L. Raczyński[7], J. Raj[1,2], S. Sharma[1,2], S. Choudhary[1,2], R. Y. Shopa[7], A. Sienkiewicz[5], M. Silarski[1,2], M. Skurzok[1,3], E. Ł. Stępień[1,2], F. Tayefi[1,2] & W. Wiślicki[7]

P. Moskal, et al., Nature Commun. 12, 5658 (2021)

Summary



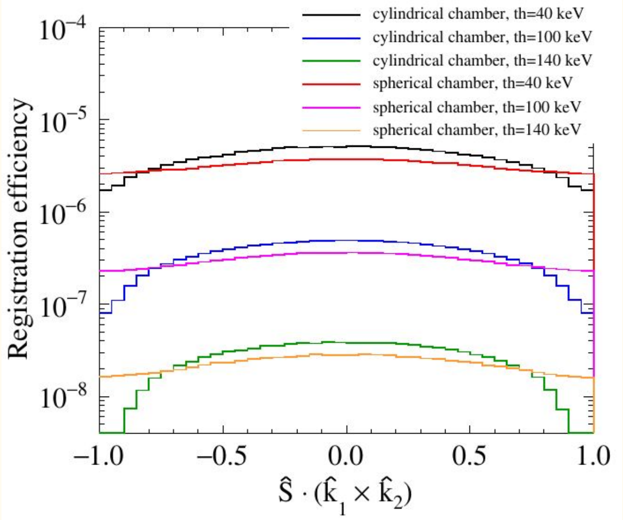
a
b
ortho-positronium
production
e⁺e⁻ → o-Ps → 3γ
e⁺
²²Na→²²Ne*e⁺ν
²²Ne + γ
Schematic cross section of the J-PET detector
c
identification of
o-Ps→3γ annihilations
Y [cm]
X [cm]
distribution of ortho-positronium annihilations
extraction of
CPT-asymmetric
angular correlation
d
Events
cosθ
S
n
θ
k1
k2
k3
o-Ps spin - decay plane
correlation

Summary and Perspectives

- With J-PET scanner, we are able to perform exclusive measurement of ortho-positronium (o-Ps) annihilation into 3 photons
  - o-Ps spin event-by-event estimation
  - o-Ps→3γ decays reconstruction including determination of the annihilation point in an extensive-size medium

- **Sub-permil precision of the CPT test reached with the first J-PET measurement (26 days): over factor of 3 better** than the previous results

- J-PET aims at the sensitivity of the CP and CPT symmetry tests at the level of 10^{-5} with the pending improvements to the setup

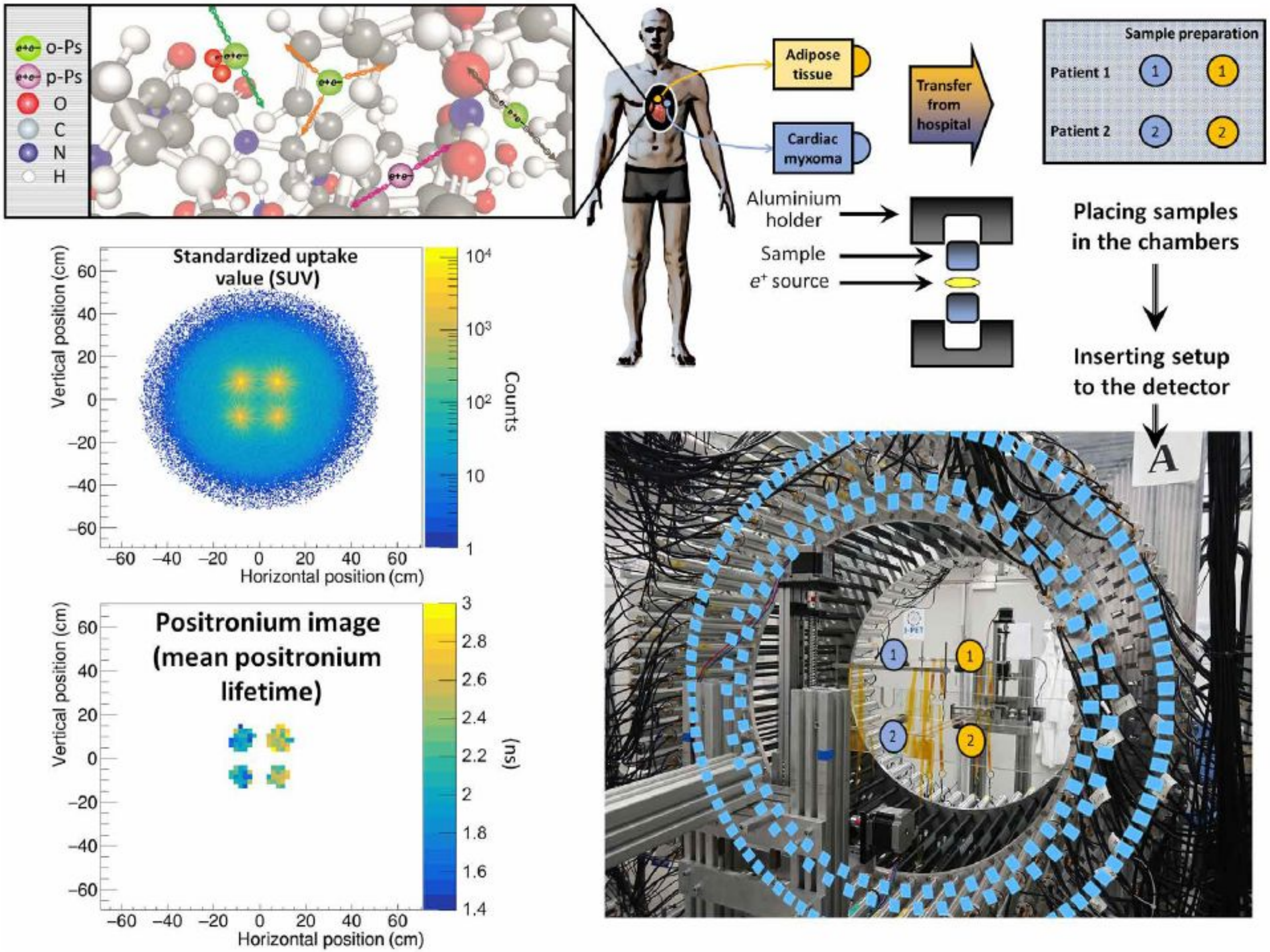


[Symmetry 12 (2020) 8, 1268]

new design of the annihilation chamber with spherical geometry, increasing the o-Ps formation probability by a factor of ~1.5

additional densely packed layer of plastic scintillators with a fully digital readout -> increase of detection efficiency by factor of 64

The first positronium imaging of a phantom built from cardiac myxoma and adipose tissue
P. Moskal, et al., Science Advances 2021; 7 : eabh4394



Thank you for your attention

J-PET

Workshop: *Is Quantum Theory exact?*, Laboratori Nazionali di Frascati, September 2019 r., with Prof Roger Penrose - Nobel Prize Winner