Three-photon positronium image reconstruction with the J-PET scanner

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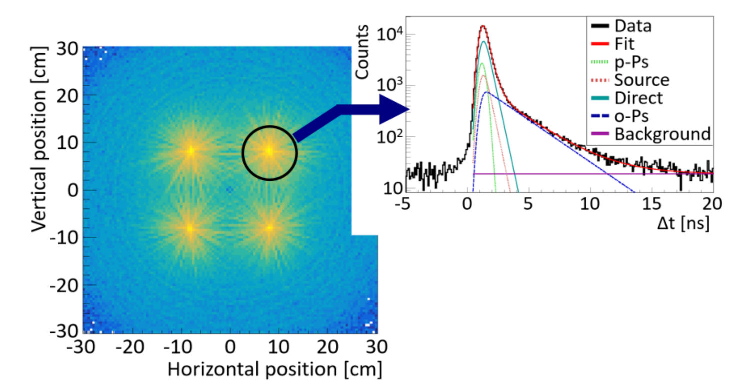
Motivation

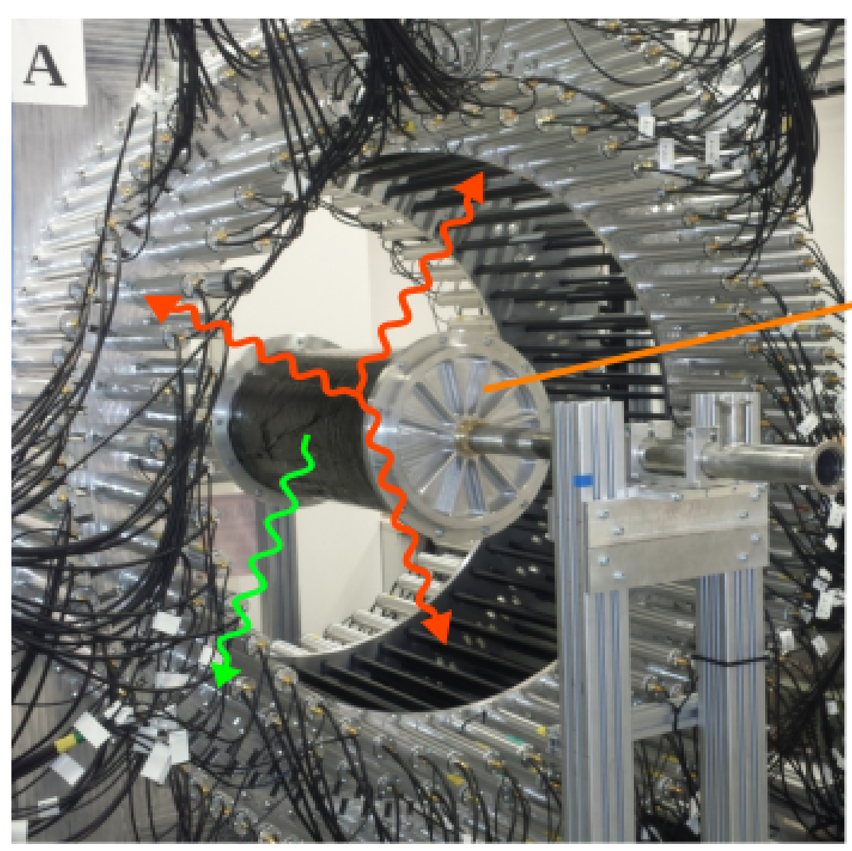
- Positronium, the e^+e^- bound state, is produced by up to 40% of positrons in a conventional PET scan. Presently, this process is not used for imaging.
- Properties of positronium formed in tissue may carry essential morphometric information complementary to functional imaging of PET [1].
- J-PET recently demonstrated the possibility to use two-photon annihilations of positronium to obtain a **positronium lifetime image** [2].
- **Relative yield of para-positronium (2γ) and ortho-positronium (3γ) annihilations** may be sensitive to sizes of inter- and intramolecular voids and oxygen levels in tissue [1].
- Requirement for the $2\gamma/3\gamma$ imaging:

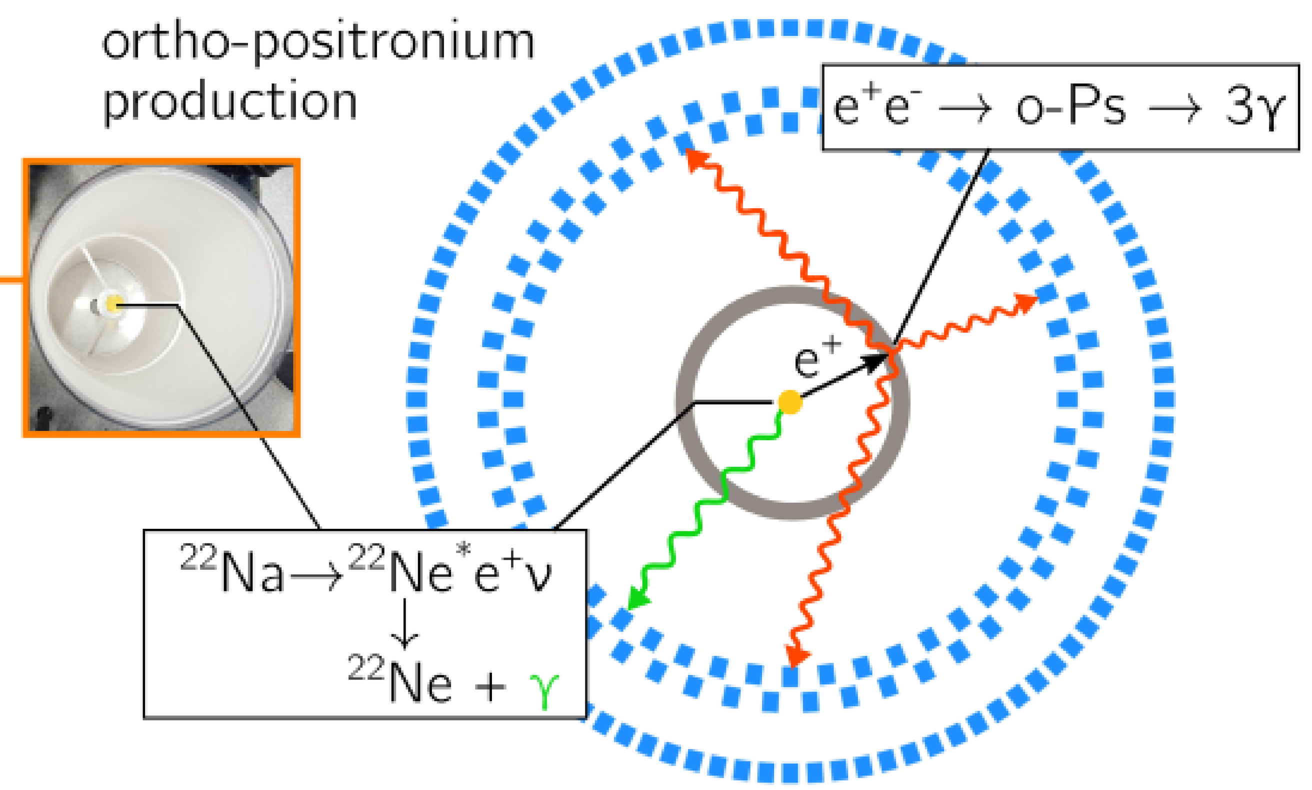
spatially-resolved reconstruction of three-photon annihilations of ortho-positronium.



Two-photon positronium lifetime imaging:
see the poster by K. Dulski.

Experimental setup

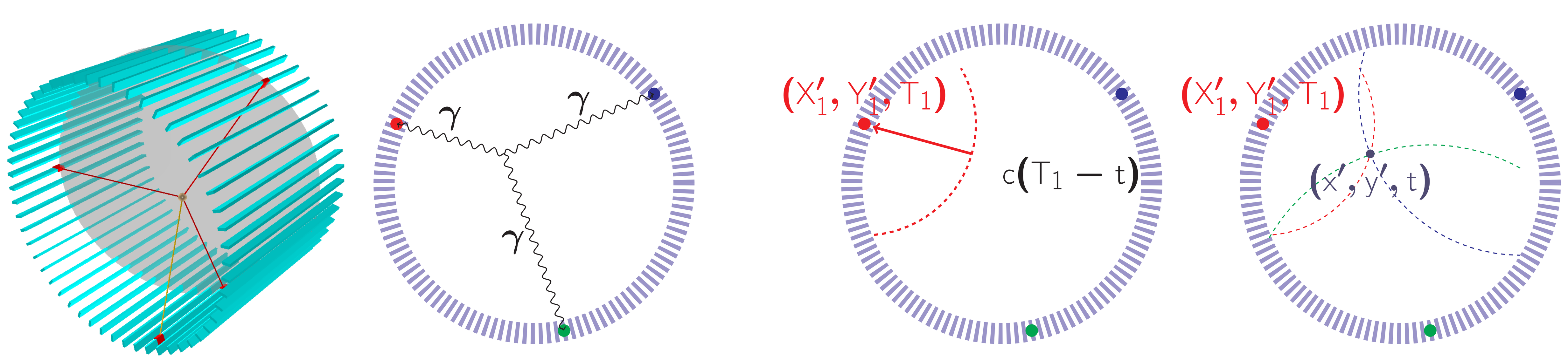




Schematic cross section of the J-PET detector

- 1st full-size J-PET scanner (50 cm AFOV)
- cylindrical (R = 12 cm) vacuum chamber coated with porous silica
- annihilation photons and prompt photons identified using Time-Over-Threshold (**see the poster by Sz. Niedźwiecki**)

Reconstruction of o-Ps→3γ events in J-PET



- analytical reconstruction based on trilateration [3] (used e.g. in GPS positioning)
- problem transformed to 2D in the o-Ps→3γ annihilation plane
- each recorded γ interaction defines a circle of possible photon origins
- annihilation point and time (x, y, t) found by solving:

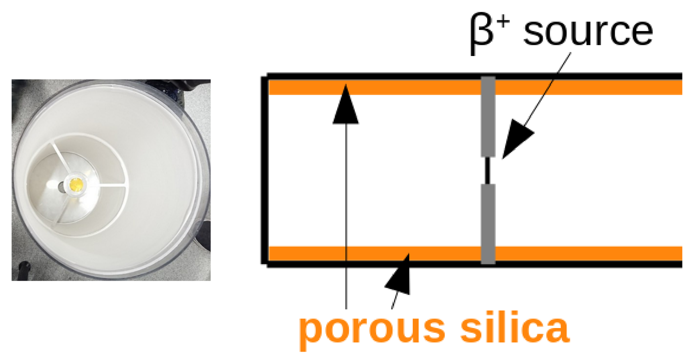
$$(T_i - t)^2 c^2 = (X'_i - x)^2 + (Y'_i - y)^2 \qquad i = 1, 2, 3$$

Results

o-Ps→3γ
1st three-photon image of an extensive object [4]

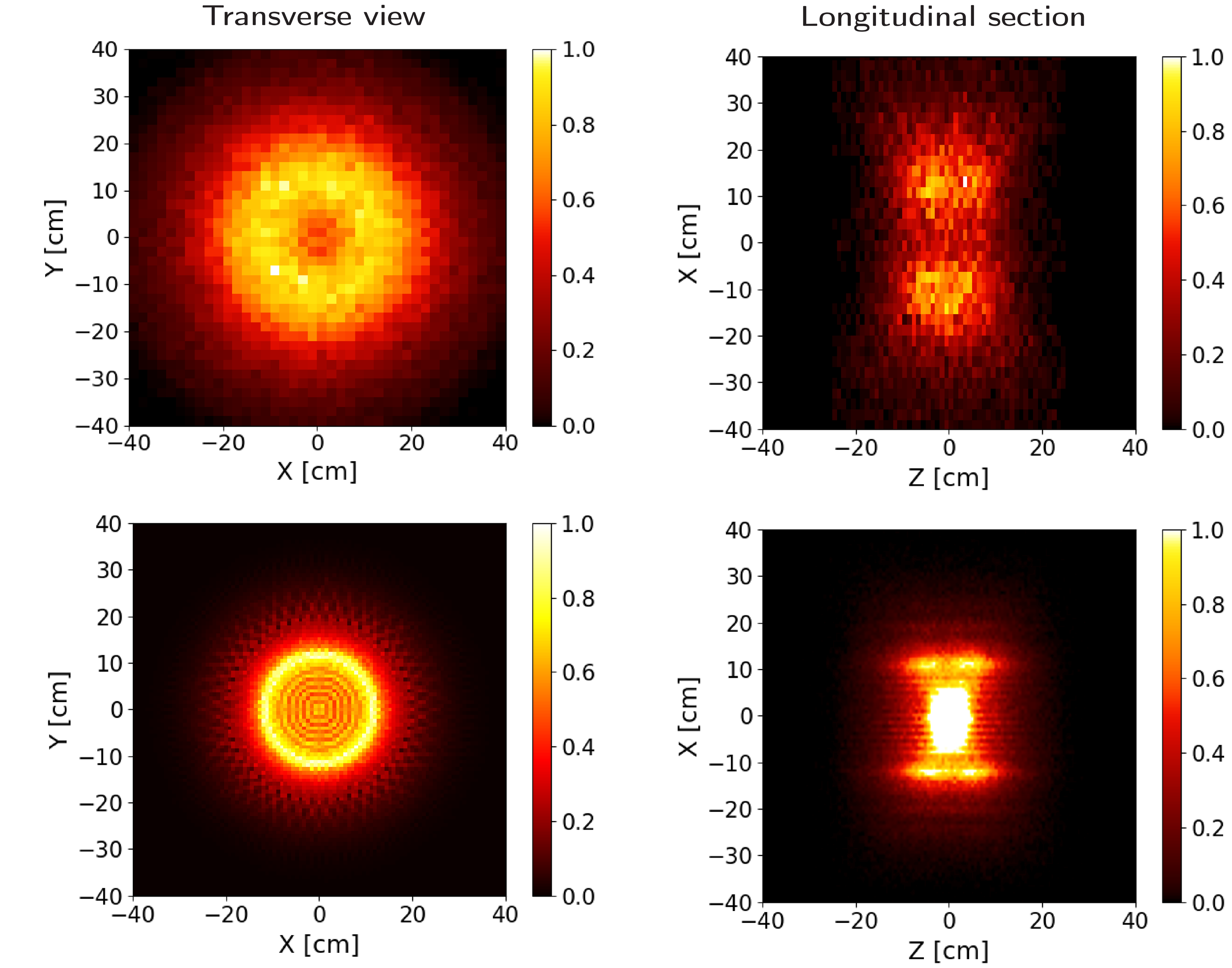
$\sigma \approx 5.3$ cm

No visible contamination from 2γ annihilations.

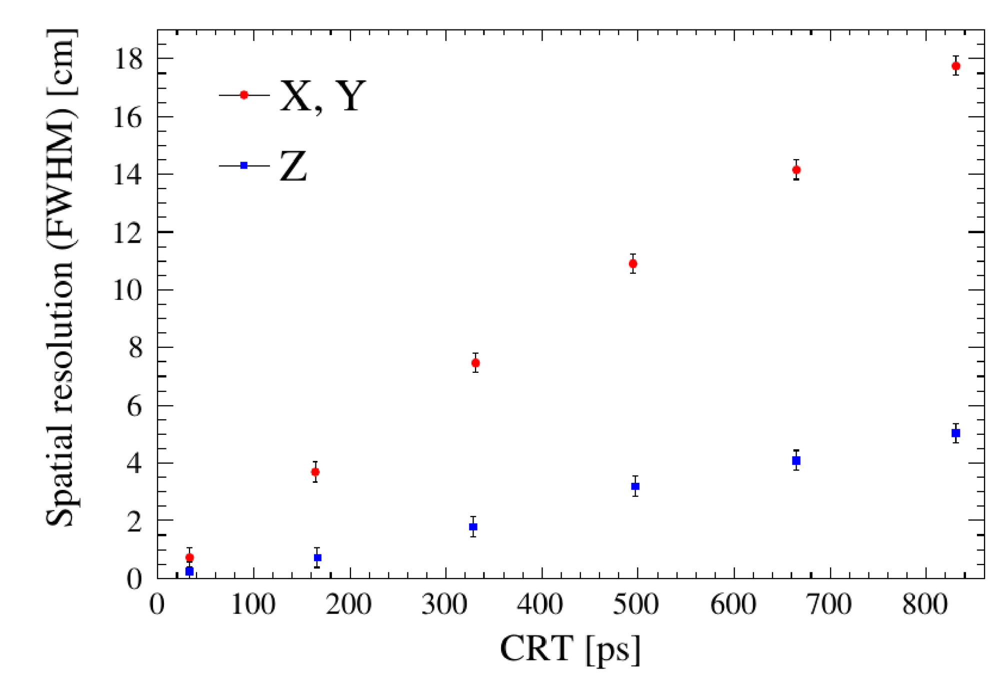


Reference:
$e^+e^- \to 2\gamma$
raw TOF images
(no statistical reconstruction)

$\sigma \approx 2.2$ cm



Prospects



Expected spatial resolution of 3γ annihilation reconstruction vs CRT of a MC-simulated scanner.

Conclusion: With the CRT-s of ∼200 ps achieved by contemporary scanners, 3γ events can be reconstructed with a resolution of a few centimeters.

References

[1] P. Moskal, B. Jasińska, E. Ł. Stępień, S. D. Bass, "Positronium in medicine and biology", Nat. Rev. Phys. **1** (2019), 527-529.
[2] P. Moskal, K. Dulski *et al.* "Positronium imaging with the novel multiphoton PET scanner", Sci. Adv. 7 (2021) eabh4394.
[3] A. Gajos *et al.* "Trilateration-based reconstruction of ortho-positronium decays into three photons with the J-PET detector," Nucl. Instrum. Meth. A **819** (2016), 54-59
[4] P. Moskal, A. Gajos *et al.* "Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography," Nature Commun. **12** (2021) no.1, 5658

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