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

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Total-body J-PET and Theranstic Center group photo, 2021-04-26
In front of Faculty of Physics, Astronomy and Computer Science of Jagiellonian University
Motivation: discrete symmetry tests with o-Ps decays

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

- bound by a central potential
- is eigenstate of the parity operator $P$

$P|Ps \rangle = (-1)^L |Ps \rangle$

- is eigenstate of the charge conjugation operator $C$

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

**Eigenstate of the CP operator**

**Para-positronium** ($p$ - Ps), $\tau = 125\text{ps}$, $^1S_0$

- Singlet state

**Ortho - positronium** ($o$ - Ps), $\tau = 142\text{ns}$, $^3S_1$

- Triplet state

- Even number of photons

- Symmetrical of charge conjugation $C$

- Odd number of photons
Testing discrete symmetries with angular correlations in o-Ps→3γ decays

Measurement the expectation value of the symmetry odd-operators

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

\[ \langle \hat{O} \rangle \overset{?}{=} 0 \quad \text{for an odd operator} \]
\[ \Leftrightarrow \text{CPT} (\hat{O}) = -1 \]
\[ \Leftrightarrow \mathcal{T} (\hat{O}) = -1 \]

\[ |\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3| \]

Required:
- the o-Ps spin determination
- of o-Ps→3γ decays selection
  (determination of photons momenta)

\[ O_{\text{CPT}} = \hat{S} \cdot (\vec{k}_1 \times \vec{k}_2) / |\vec{k}_1 \times \vec{k}_2| = \cos \Phi \]

<table>
<thead>
<tr>
<th>Operator</th>
<th>C</th>
<th>P</th>
<th>T</th>
<th>CP</th>
<th>CPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{S} \cdot \vec{k}_1 )</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>( \hat{S} \cdot (\vec{k}_1 \times \vec{k}_2) )</td>
<td>+</td>
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<td>+</td>
<td>−</td>
</tr>
<tr>
<td>( (\hat{S} \cdot \vec{k}_1)(\hat{S} \cdot (\vec{k}_1 \times \vec{k}_2)) )</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>( \vec{k}_1 \cdot \vec{e}_2 )</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>( \hat{S} \cdot \vec{e}_1 )</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>( \hat{S} \cdot (\vec{k}_2 \times \vec{e}_1) )</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

Previous measurements

\[
C_{\text{CPT}} = (2.6 \pm 3.1) \times 10^{-3}
\]

Gammasphere
PRL. 91 (2003) 263401
\[
\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)
\]
\[
P_{e^+} = \frac{\nu}{c} \cdot 0.686
\]
Limiting positron emission direction
1 Mbq $\beta^+$ emitter activity
4$\pi$ detector but low angular resolution

\[
C_{\text{CP}} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}
\]
Yamazaki et al.
PRL 104 (2010) 083401
\[
(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))
\]
Polarized o-Ps using external B field
Inclusive measurement
Only certain angular configurations

Courtesy of A. Gajos
Motivation: discrete symmetry tests with o-Ps decays

- Discrete symmetries are scarcely tested with leptonic systems:
  - Neutrino oscillations: Dirac phase, $\delta CP \sim 3\sigma$ level [T2K, Nature 580 (2020) 339]

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

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 $\beta^+ {^{22}\text{Na}}$ source placed in the center

J-PET detector at Jagiellonian University in Kraków, Poland

- 192 EJ-230 scintillators: 7x19x500 mm³;
- 384 R9800 photomultipliers;
- 85 cm radius;
- 1536 channels;
- multithreshold digital electronics;
- the novel trigger-less DAQ;

o-Ps spin estimation:

* \(e^+\) spin estimated event-by-event recording multiple geometrical configurations
* effective polarization depends on o-Ps→3γ vertex resolution
* vacuum in the chamber assures that \(e^+\) is not going to decay before reaching inner wall

\[
P_{e^+} \approx \frac{\nu}{c} \cdot \frac{1}{2} (\cos \alpha + 1)
\]

\[
P_{e^+} = \frac{N_{+1/2}^{e^+} - N_{-1/2}^{e^+}}{N_{+1/2}^{e^+} + N_{-1/2}^{e^+}}
\]

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 $\gamma$.

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

[A. Gajos et al., NIM A 819 (2016), 54-59]
J-PET vs previous measurements

\[ C_{\text{CPT}} = (2.6 \pm 3.1) \times 10^{-3} \]

\[ C_{\text{CP}} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3} \]

Gammasphere

\[ \vec{S} \cdot (\vec{k}_1 \times \vec{k}_2) \]

\[ P_{e^+} = \frac{v}{c} \cdot 0.686 \]

Limiting positron emission direction

1 M bq \( \beta^+ \) emitter activity

4\( \pi \) detector but low angular resolution

J-PET

Recording multiple geometrical configurations

e+ spin estimated event-by-event

\[ P_{e^+} \approx \frac{v}{c} \cdot 0.91 \]

Polarized o-Ps using external B field

Inclusive measurement

Only certain angular configurations

- Plastic scintillators = fast timing
  → using high \( \beta^+ \) emitter activity
  (tested up to 10 M bq)
- 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 γ deposited energy

⇐ o-Ps presence in positron lifetime distribution
**Secondary Compton scatterings:**

\[ \delta_{ij} = |d_{ij} - c\Delta t_{ij}| \]

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

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**2\(\gamma\) from the \(\beta^+\) source setup coincident with de-excitation photon:**

- distance between the \(\beta^+\) source location and the closest hypothetical \(2\gamma\) annihilation point on a LOR between two recorded photon interactions
- the sum of the two smallest angles between azimuthal coordinates of the recorded \(\gamma\) interaction points
Determination of the CPT - asymmetric observable

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

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

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

**MC simulations**

\[ \uparrow \]

expected asymmetry in case of CPT violation

\[ \leftarrow \]

efficiencies evaluated with MC are symmetric in \( \cos \theta \)
\[ O_{\text{CPT}} = \hat{S} \cdot (\vec{k}_1 \times \vec{k}_2) / |\vec{k}_1 \times \vec{k}_2| = \cos \phi \]

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

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

\[ \frac{\int N(\cos \theta) \cos \theta}{\int N(\cos \theta)} \]

~2 mln of identified o-Ps \( \rightarrow \) 3\gamma annihilations

\[ \langle O_{\text{CPT}} \rangle = 0.00025 \pm 0.00036 \]

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

\[ C_{\text{CPT}} = \langle O_{\text{CPT}} \rangle / P = 0.00067 \pm 0.00095 \]


stat error : 3.3 x 10^{-4} 
syst error: 1.4 x 10^{-4}
Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography

P. Moskal1,2, A. Gajos1,2, M. Mohammed1, J. Chhokar1,2, N. Chug1,2, C. Curceanu1,2,3, E. Czerwiński1,2, M. Dadgar1,2, K. Dulski1,2, M. Gorgol1,4, J. Goworek1,5, B. C. Hiesmayr2,6, B. Jasińska4, K. Kacprzak1, Ł. Kapłon1,2, H. Karimi1,2, D. Kisielewska1, K. Klimaszewski7, G. Korcyl1,2, P. Kowalski7, N. Krawczyk1,2, W. Krzemień8, T. Kozik1, E. Kubicz1,2, S. Niedźwiecki1,2, S. Parzych1,2, M. Pawlik-Niedźwiecka1,2, L. Raczyński7, J. Raj1,2, S. Sharma1,2, S. Choudhary1,2, R. Y. Shopa7, A. Sienkiewicz1,5, M. Silarski1,2, M. Skurzok1,3, E. Ł. Stępień1,2, F. Tayefi1,2 & W. Wiślicki7

Summary
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

\[ C_{\text{CPT}} = \frac{\langle O_{\text{CPT}} \rangle}{P} = 0.00067 \pm 0.00095 \]
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
Thank you for your attention