Tests of discrete symmetries in positronium decays with the J-PET detector

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on behalf of the J-PET Collaboration

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Outline

► Discrete symmetries tests with positronium
► The J-PET detector and reconstruction techniques
► Commissioning and upgrades
► Conclusions
Positronium (Ps)

para-positronium (p-Ps) \[ \uparrow \downarrow \quad 2n\gamma \quad \text{CP}=+1 \quad \tau \approx 0.125\text{ns} \]
ortho-positronium (o-Ps) \[ \uparrow \uparrow \quad (2n+1)\gamma \quad \text{CP}=-1 \quad \tau \approx 142\text{ns} \]

- Purely leptonic (e+e-) bound state
- C, P, CP operators and \( H \) eigenstate
- The lightest atom
- Undergoes self-annihilation
- e+ and e- do not decay into lighter particles via weak interaction, \( 10^{-14} \) violation level due to the weak interaction
  
  [ M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008) ]

- No charged particles in the final state (\( 2\times10^{-10} \) radiative corrections)
- No discrete symmetry violation observed in non-quark system, for e+e- system: Standard Model \( 10^{-9} \) – upper limits \( 10^{-3} \) for T, CP, CPT

\[ ^{22}\text{Na} \rightarrow ^{22}\text{Ne}^* + e^+ + \nu_e \]

\[ ^{22}\text{Ne}^* \rightarrow ^{22}\text{Ne} + \gamma (1.247 \text{ MeV}, \tau \approx 3.7 \text{ ps}) \]
\[ C_{CP} = \left\langle \left( S \cdot k_1 \right) \left( S \cdot (k_1 \times k_2) \right) \right\rangle = 0.0013 \pm 0.0022 \]


\[ C_{CPT} = \left\langle S \cdot (k_1 \times k_2) \right\rangle = 0.0026 \pm 0.0031 \]


SM: \(10^{-9} - 10^{-10}\) effects of final state interaction


With the J-PET detector we are sensitive to the CP violating effects at the level of \(10^{-5}\). [J-PET: P. Moskal et al., Acta Phys. Polon. B47 (2016) 509]
J-PET (Jagiellonian PET)

\[ \Delta x = (t_l - t_r) \frac{c}{2} \]
\[ \Delta l = (t_2 - t_1) \frac{v}{2} \]


J-PET
192 detection modules arranged in 3 layers
- 19x5x500 mm³ EJ-230 scintillator strips + Hamamatsu R9800 photomultipliers.

Novel digital front-end electronics probing signals at multiple thresholds.
[M. Palka et al. JINST 12 (2017) no.08, P08001]

Trigger-less and reconfigurable DAQ system.

Annihilation gamma quanta hit time measurement:
$\sigma_t(0.511 \text{ MeV}) \sim 125 \text{ ps.}$ [P. Moskal et al., Nucl.Instrum.Meth. A775 (2015) 54-62]

Gamma quanta energy resolution:
$\sigma_E/E = 0.044/\sqrt{E(\text{MeV})}$ [P. Moskal et al. Nucl.Instrum.Meth. A764 (2014) 317]

Resolution of photons relative angles measurement $\sim 1^\circ$.

$\sigma$-ps spin and photon polarization measurement.
\[ ^{22}\text{Na} \rightarrow ^{22}\text{Ne}^* + e^+ + \nu_e \]

\[ ^{22}\text{Ne}^* \rightarrow ^{22}\text{Ne} + \gamma (1.247 \text{ MeV}, \tau \approx 3.7 \text{ ps}) \]

Determination of o-Ps polarization

\[ P = \frac{v}{c} \left(1 + \cos \alpha \right)/2 \]
\[ \approx 98\% \]
Determination of o-Ps polarization

Determination of energy of annihilation $\gamma$

\[
E_1 = -2m_e \frac{-\cos \theta_{13} + \cos \theta_{12} \cos \theta_{23}}{(-1 + \cos \theta_{12})(1 + \cos \theta_{12} - \cos \theta_{13} - \cos \theta_{23})},
\]
\[
E_2 = -2m_e \frac{\cos \theta_{12} \cos \theta_{13} - \cos \theta_{23}}{(-1 + \cos \theta_{12})(1 + \cos \theta_{12} - \cos \theta_{13} - \cos \theta_{23})},
\]
\[
E_3 = 2m_e \frac{1 + \cos \theta_{12}}{1 + \cos \theta_{12} - \cos \theta_{13} - \cos \theta_{23}}.
\]

Determination of polarization of anihilation $\gamma$

\[
\frac{d\sigma}{d\Omega}(E, \theta, \eta) = \frac{r_0^2}{2} \left( \frac{E'}{E} \right)^2 \left( \frac{E}{E'} + \frac{E'}{E} - 2\sin^2\theta\cos^2\eta \right)
\]

\[
E'(E, \theta) = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}
\]

\[ \theta_{23} > 180 - \theta_{12} \]
\[ \theta_{23} = 180 - \theta_{12} \]
\[ \theta_{23} < 180 - \theta_{12} \]

Simulations


EXPERIMENT

Run-1
analysed by K. Kacprzak

3 Hit angle difference

\[ \theta_{12} < \theta_{23} < \theta_{31} \]
Commissioning

Courtesy of M. Pawlik-Niedźwiecka
Ps detection

RUN2 with annihilation chamber with XAD4 material (longest mean lifetime around 90 ns), 40% of all data

Time difference = \((\text{Time}_1 + \text{Time}_2)/2 - \text{Time}_{\text{deex}}\)

Counts

<table>
<thead>
<tr>
<th>Entries</th>
<th>409980</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>7.77</td>
</tr>
<tr>
<td>RMS</td>
<td>70.5</td>
</tr>
</tbody>
</table>

Courtesy of K. Dulski
Ps detection

Result for ~20s data-taking

Central region in Z excluded

Central region in Z included
CPT test

\[ A = \frac{N_+ - N_-}{N_+ + N_-} \]

\[ C_{CPT} = A / \langle P \rangle \]

\[ C_{CPT} = 0.0026 \pm 0.0031 \quad \text{(for} \; \vec{S} \cdot \vec{k}_1 \times \vec{k}_2) \]


\[ k_1 > k_2 > k_3 \]

- \( \langle P \rangle \): average polarization
- Gammasphere: 43% for \(^{22}\text{Na}\) and 61% for \(^{68}\text{Ge}\). Determined on hemisphere
- J-PET: the uncertainty of determination of positron direction will amount to about \(15^\circ\)

<table>
<thead>
<tr>
<th></th>
<th>J-PET</th>
<th>Gammasphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector material</td>
<td>BC-420</td>
<td>HPGe and BGO</td>
</tr>
<tr>
<td>Time resolution</td>
<td>80 ps</td>
<td>4.6 ns</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>(1.4^\circ/0.5^\circ)</td>
<td>(4^\circ/4^\circ)</td>
</tr>
<tr>
<td>Source activity</td>
<td>10 MBq</td>
<td>1 MBq (limited by pile-ups)</td>
</tr>
</tbody>
</table>
CPT test

- $C_{CPT} = 0.0026 \pm 0.0031$ (for $\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$)  

- Dependency between number of reconstructed o-Ps\,$\rightarrow\,$3$\gamma$ events and the amplitude of $\mathcal{CPT}$ violating asymmetry uncertainty (red line). Plot is made assuming detection parameters as in Gammashpere detector. Result obtained by Vetter and Freedman is denoted by black square.

- $R_{o-Ps\rightarrow3\gamma} = \mathcal{A} \cdot f_{o-Ps\rightarrow3\gamma} \cdot \epsilon_{det(th)} \cdot \epsilon_{ana}$,
  - $\mathcal{A}$ - source activity
  - $f_{o-Ps\rightarrow3\gamma}$ - fraction of o-Ps\,$\rightarrow\,$3$\gamma$ annihilation
  - $\epsilon_{det(th)}$ - detection efficiency
  - $\epsilon_{ana}$ - analysis efficiency

- XAD-4 (10MBq, th=50keV):  
  $R_{o-Ps\rightarrow3\gamma} = 25$ events/s  
  $\approx 1.5 \times 10^7$ events/week

- around 1.5 year of measurement is required to improve the previous result by an order of magnitude
Ps detection

Run 3 chamber, R ≈ 7 cm
No o-Ps production medium
2 days of measurement

Run 6 chamber, R ≈ 12 cm
Walls coated with a porous polymer
180 days of measurement

Result for ~48h data-taking

Result for ~6h data-taking
CPT test

180 days of measurement

Result for ~20h data-taking

Mean 0.0048 ± 0.0079

\[ S \cdot (k_1 \times k_2) / (|S| |k_1 \times k_2|) \]

Counts

Preliminary

Courtesy of A. Gajos
Upgrades
Upgrades – efficiency map
Upgrades
Conclusions

- lack of experimental data on discrete symmetries studies in the leptonic sector;

- C, T, CP and CPT tests in the o-Ps decays at the level of $10^{-5}$ possible with the J-PET detector;

- the J-PET detector during commissioning phase with first measurements' results.
Thank you for attention